Modelling Phosphorus Management in the Bay of Quinte, Lake Ontario in the Past, 1972 to 2001, and in the Future

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Modelling Phosphorus Management in the Bay of Quinte, Lake Ontario in the Past, 1972 to 2001, and in the Future.

by

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ABSTRACT

Minns, C.K. and J.E. Moore. 2004. Modelling phosphorus management in the Bay of Quinte, Lake Ontario in the past, 1972 to 2001, and in the future: 2695

A simple input-output phosphorus model was developed and implemented for the Bay of Quinte. The model was based on that described by Minns (1986), whereby a three-section model of the bay was applied to the upper, middle and lower Bay of Quinte. The model was implemented using STELLA modelling software with a daily time step for the period 1972-2001. Hydrology, stream concentrations, and sewage treatment plant (STP) flows and concentrations were reproduced. Future scenarios cover the period 2002-2031. Key parameter estimates can be changed to examine the effects of uncertainties on model predictions. Simulation output includes daily values for all compartments and major flows as well as annual and summer mean concentrations by years in the water column and surface sediment compartments. The model produced a high level of agreement with observations for the calibration period. The future scenario results indicated the following:

a) The recovery process is expected to continue after 2001 as long as 2001 STP flows continue at Certificate of Approval concentrations. Under these conditions, the water concentrations will be, by 2031, close to steady state, within 0.2 $\mu g\ L^{-1}$ of their final value.

b) With point source loading set at 2001 levels and zebra mussel effects at median levels, the model predicts that under the low river flow scenario (projected climate change effects), mean summer upper bay phosphorus concentrations will increase by 9 to 13 $\mu g\ L^{-1}$ above the baseline scenario – a level well above the Remedial Action Plan target phosphorus concentration for the upper bay.

c) These results suggest that currently approved final effluent concentrations will have to decrease at sewage treatment plants discharging to the Bay of Quinte before flows from these plants attain their rated capacities. An upper bay point-source loading limit of 15 kg P day^{-1} will be necessary to safeguard water quality in the Bay of Quinte for the long-term.

RÉSUMÉ

Minns, C.K., et J.E. Moore. 2004. Modélisation de la gestion du phosphore dans la baie de Quinte, lac Ontario, dans le passé, de 1972 à 2001, et dans l'avenir: 2695

Un modèle simple d'entrée-sortie du phosphore a été élaboré et mis en œuvre pour la baie de Quinte. Le modèle se fondait sur celui qui avait été décrit par Minns (1986), et qui découpait la baie en trois sections (inférieure, moyenne et supérieure). Le modèle a été mis en œuvre à l'aide du logiciel de modélisation STELLA avec un pas de temps journalier pour la période 1972-2001. Le modèle reproduisait les conditions hydrologiques, les concentrations dans les cours d'eau et les débits et concentrations à la sortie des stations de traitement des eaux usées. Les scénarios prospectifs couvrent la période 2002-2031. Il est possible de modifier les estimations des paramètres clés pour examiner les effets des incertitudes sur les prédictions du modèle. Les résultats de la simulation donnent notamment les valeurs journalières pour tous les compartiments et les écoulements principaux ainsi que les concentrations moyennes annuelles et estivales par année dans la colonne d'eau et dans les sédiments de surface. Le modèle a atteint un niveau élevé de concordance avec les observations pour la période d'étalonnage. Les résultats des scénarios prospectifs donnent les indications suivantes :

a) Le processus de rétablissement devrait se poursuivre après 2001 pour autant que les rejets des stations de traitement des eaux usées continuent à respecter les concentrations fixées par les certificats d'approbation. Dans ces conditions, les concentrations dans l'eau devraient être, d'ici 2031, proches de l'équilibre, à moins de 0,2 $\mu g\ L^{-1}$ de leur valeur finale.

b) Avec une charge des sources ponctuelles fixée aux niveaux de 2001 et des effets des moules zébrées fixés à un niveau moyen, le modèle prévoit que, dans le scénario de faible débit des cours d'eau (ce qui correspond aux effets prévus du changement climatique), les concentrations estivales moyennes de phosphore dans la section supérieure de la baie augmenteront de 9 à 13 $\mu g\ L^{-1}$ au-dessus du scénario de base – niveau nettement supérieur à la concentration cible de phosphore du plan d'assainissement pour la section supérieure de la baie.

c) Ces résultats permettent de penser que les concentrations dans l'effluent final actuellement approuvées devront être réduites aux stations de traitement des eaux usées qui rejettent leurs effluents dans la baie de Quinte avant que ces stations atteignent leur capacité nominale de rejet. Il sera nécessaire de fixer à 15 kg de P par jour la limite de charge des sources ponctuelles pour protéger à longue échéance la qualité de l'eau dans la baie de Quinte.

INTRODUCTION

Minns et al. (1986) published estimates and analysis of nutrient budgets for the Bay of Quinte, an embayment in the northeast corner of Lake Ontario, covering the period 1965-81. The Bay of Quinte had undergone major eutrophication in the late 1950s and in the 1960s. In the early 1970s, the Bay of Quinte became one of many targets for point source phosphorus control around the Great Lakes. Major upgrades were instituted in the winter of 1977-78. In 1972, a multi-agency group, Project Quinte, began a long-term study of phosphorus management in the bay and its consequences for many biotic elements in the ecosystem. In 1986, the Project Quinte group published a collection of papers documenting ecosystem changes in the period 1972 to 1981 (Minns et al., 1986). Since the major reductions in point source phosphorus inputs took place in 1977-78, significant further reductions in point source loading have been achieved. The work of the Project Quinte group has continued and in recent years has shifted focus as dreissenid mussels invaded in the mid-1990s. A recent reanalysis of the water and phosphorus budgets for the period 1972-2001 in the Bay of Quinte (Minns et al. 2004) showed that assumptions and patterns reported by Minns et al. (1986) have continued given allowance for changing runoff, point source loadings and other effects related to the establishment of dreissenid mussels.

The Ontario Ministry of Environment and the Bay of Quinte Restoration Council, which oversees the on-going monitoring and implementation of the Remedial Action Plan, commissioned both the recent reanalysis of water and phosphorus budgets (Minns et al. 2004) and the development of a simple phosphorus model of the Bay of Quinte as foundations for a long-term P management plan to protect the Bay from re-emergence of eutrophication as a threat to the health of the ecosystem. The purpose of this report is to describe and update, using contemporary ecosystem modelling software, the application of a phosphorus input-output model developed by Minns (1986). The application is intended first to simulate phosphorus budgets in the bay for the period 1972-2001. Second, it is intended to provide a method of forecasting future in-bay phosphorus concentrations given various assumptions. There are several questions that need to be assessed by the agencies regulating phosphorus loading to the bay in order to develop a phosphorus management plan, including:

- Since the new and upgraded sewage treatment facilities have higher flow capacities to allow for future population growth, will operation of all those point sources at 100 percent capacity keep water quality in the bay at preferred levels?
- As emerging climate change signals indicate a warmer, drier future, will reduced river flows compromise phosphorus management plans based on past hydrologic conditions?
- As the recent rapid invasion and colonization of the Bay of Quinte by dreissenid mussels (zebra and quagga species) appears to be affecting phosphorus dynamics, does the expected persistence of high mussel abundances impact future phosphorus management?
- As much effort has been directed more recently to control of diffuse nutrient and sediment loadings to complement point sources controls, what role might diffuse load control have in phosphorus management in the Bay of Quinte?

Models, such as the one presented here, provide a basis, built on the best available understanding of nutrient dynamics, for answering these questions. Multiple conditions and factors inevitably interact to determine the ultimate ecosystem outcome; computer modelling approaches to these questions will optimize the generation of answers to such questions.

MATERIALS AND METHODS

OVERVIEW OF MODEL

The application of the model described by Minns (1986) was developed using version 8 of the systems modelling package Stella® (High Performance Systems, Inc., now ISEE Systems). The model developed consisted of an independent model for each of the three upper, middle and lower bay sections, coupled by water outflow from one section to the next. The model was developed initially at the intermediate level of information flows, compartments, and controls in Stella (Figures 1 and 2). At the lower level, the actual equations were formulated and parameters entered while at the higher level the user interfaces were developed. Considerable documentation was built into the program by element. Each section model was comprised of:

a) a section water column phosphorus store with:
   - phosphorus input via inflow from the upstream section, tributary flows, precipitation, sewage treatment plant (STP) point source flows, and reflux from the bottom sediments
   - phosphorus output via outflow to the next section and settling to the bottom

b) a section sediment phosphorus store with:
   - phosphorus input via settling from the water column
   - phosphorus output via reflux to the water column and loss to deeper sediment layers through burial

The resulting model was set up to run on a daily time-step over the period from 1972 to 2031, where each of those 60 years was 365 days long. In that time span, the period from 1972 to 2001 was considered to be the "historical" period and was parameterised using the same input data used in the budget analysis done by Minns et al. (2004). The period from 2002 to 2031 was considered to be the "future" period and was parameterised using aggregations of the budget input data, such that the model input data remained the same from year to year. The exception to the latter was parameterization of point source loads which was provided by links to an external data source, to allow gaming on a year-to-year basis with those inputs.

The details of the parameterization process are provided below. Historical estimates were used to parameterize the future period of the model. Details regarding the ultimate source of the data described are generally not provided and should be sought in Minns et al. (2004).

PARAMETERIZATION OF HISTORICAL MODEL PERIOD

Ideally one would parameterize the historical period at the same daily time resolution at which the model was to run, requiring that it be possible to store for each parameter a time-series of 10950 (30 x 365) daily values. Unfortunately the only mechanism in Stella for storing such time series (the "graphical function") was limited to series with a maximum of 1500 values. Thus, much of what follows describes what was done to condense 10950 values to something as close to but not greater than 1500 values.

Water Levels

Hourly water levels at Kingston, Ontario were available for the whole historical period with very few gaps in the time series, so that the average observation frequency was 23.99 per day. The time series consisted of elevations relative to the Lake Ontario low-water datum (74.2 metres above the International Great Lakes Datum for 1985 (IGLD85). These were averaged by

day, the sample size being 24 for all but seven days, for which it ranged from 7 to 23. Five consecutive days in May, 1988 were missing data altogether and were assigned the average of the 597 other values available for that month. All leap days were dropped from the time series, leaving 10950 values. The resulting daily values were stored in the model in groups of four years per graphical function, so that no condensation was required.

Tributary Flows

Daily flows (m^3 day^{-1}) were available for the whole historical period for each of four tributaries (Trent River, Moira River, Salmon River, and Napanee River) draining into the upper bay, and for Wilton Creek draining into the middle bay. Leap days were again dropped. An early attempt to store the resulting daily data using the same technique as employed for water levels proved to be unwieldy. Each river's time series was instead rendered as a series of blocks 8 days in length, and an average flow for each block was computed, thereby creating a condensed time series with 1369 values. For a given river, the flow for each day was then the average value for the time block corresponding to that day, so that a stepped time series resulted. The model combined these flows to produce a total daily tributary inflow by bay section, accounting for miscellaneous drainages using Wilton Creek equivalents as described in Minns et al. (1986, 2004).

Precipitation and Evaporation

Historical daily total precipitation data (0.1 mm) were available for the Trenton weather station (#6158875) and were imported after setting trace amounts to zero, scaling to metres per day, and dropping leap days. These data were stored as averages by 8-day block, as described above for tributary flows.

No attempt was made (as was done in Minns et al. (2004)) to distinguish between snowfall and rainfall , or to delay the contribution of snowfall to the water budget. Evaporation was arbitrarily set as equal to precipitation, regardless of the time of year. The resulting precipitation values were applied to the whole bay.

Section Areas and Volumes

Fixed section areas were used as in Minns et al. (1986,2004): upper bay =136.388 km^2, middle bay = 49.179 km^2, and lower bay = 71.835 km^2. Daily volume changes were simply the product of these areas and daily level changes, so that each section's profile is considered to be cylindrical within the range of observed water levels. Daily estimates of section volumes were obtained as the sum of an initial volume plus the product of the section area times the difference between the daily level and an initial level. The initial level (0.320833 metres) is just the first value in the historical levels series described above, whereas the initial volumes (millions of m^3) were estimated as described in Minns et al. (2004): upper bay = 522.6387, middle bay = 271.9802, and lower bay = 1780.092 $x10^6$ m^3, respectively.

Section Backflows

An early attempt to predict section backflows from levels data proved to be fruitless, so instead backflows computed for the Middle and Lower Bays in Minns et al. (2004) were used to develop estimates of section backflows for the model. The monthly values generated by their work were averaged by month and bay section over the 30-year historical period to produce a single composite graphical function for each bay section, providing backflow (m^3 day^{-1}) for each

day as the average for the month to which that day belonged. Because of the importance of backflows in the phosphorus budget for the Middle and Lower Bays, these graphical functions were brought out as part of the user interface of the model so that they could be altered by the model user at will.

Tributary Phosphorus Input Concentrations

The budget work in Minns et al. (2004) employed rating curves to provide daily estimates of tributary phosphorus loads from tributary flows. These historical values were re-expressed for use in the model as daily total phosphorus concentrations ($\mu g.L^{-1}$) by dividing by the corresponding flow values. In some instances their rating curves employed a second term based on a (Year-1971). These values were not used in the model, so that all P loading estimates result from rating curves based on observed tributary concentrations only. Leap days were removed, and the remaining 10950 values (1972-2001) were stored by river as averages by 8-day block as described above for the flows data.

For Wilton Creek, a sequence of dates in August, 1988 and another in August, 2001 had zero flows, these were given concentrations equal to that just before and just after the sequence.

Atmospheric Phosphorus Input Concentrations

A constant value for total phosphorus concentration in precipitation was employed for both the historical and future periods. The model default value is based on the average of monthly values from the budget work of Minns et al. (2004), who used concentrations based on regression estimates. The average of their estimates for the historical period was 12.7 $\mu g.L^{-1}$ which was rounded up to 15 for use in the model. This value is exposed to the model user for change as desired within the range 0 to 50 $\mu g.L^{-1}$.

Point Source Phosphorus Inputs

Historical point source loads (kg day^{-1}) by bay section were based on a composite of a number of data sources as described in Minns et al. (2004). The monthly load estimates they used were converted to equivalent daily loads, leap days were removed, and the remaining data stored by bay section as averages by 8-day block.

Note that these estimates were dominated by sewage treatment plant (STP) inputs, though up to 1982 some industrial inputs were included. Thereafter, it was assumed that the industrial inputs were included either in the tributary inputs or the STP inputs.

Lake Ontario Phosphorus Concentrations

An estimate of the concentration of total phosphorus ($\mu g.L^{-1}$) in Lake Ontario was needed to account for the effects of backflows from Lake Ontario on the phosphorus budget of the Lower bay. The historical values used in the model were based on monthly mean values compiled from a number of sources as described by Minns et al. (2004). These are represented in the model by annual means based on simple averages by year of monthly concentrations.

PARAMETERIZATION OF FUTURE MODEL PERIOD

Most parameters in the future period of the model were given daily values for a 365-day year, repeated for every year in the interval 2002 to 2031. Gaming was restricted in this instance to a choice of one of 5 scenarios, providing a range of value sets varying between extremes observed in the historical data, plus a user-defined scenario. Other parameters are presented by a single constant value, adjustable by the model user within a fixed range of possibilities.

The exception to the above is the treatment afforded to future point source load estimates where future point source inputs are provided by links to an external data source. That source allows gaming with loads on an annual basis.

Water Levels

For any given run of the model, future water levels were represented as a single 365-day time series which remained the same from year to year. The actual values in the time series depended on a choice of a levels scenario.

To obtain the levels scenarios, aggregate time series of water levels were developed by subjecting the daily historical series to an analysis in which cumulative distributions of the 30 values (1972 to 2001) by day of the year were developed and percentile values extracted. From this, a 365-day time series representing the median value by day was generated as a "typical" scenario. Similarly, time series representing the 10^{th}, 25^{th}, 75^{th}, and 90^{th} percentiles were generated as "very low levels", "low levels", "high levels", and "very high levels" scenarios. A sixth all-zero scenario was provided as a user-defined scenario. Choice from among the six scenarios was provided to the model user along with a graphical means for defining the values in the sixth scenario.

Tributary Flows

A corresponding analysis of historical tributary flows was done to generate, by river, "very low flows", "low flows", "typical", "high flows", and "very high flows" scenarios. As above, choice from among the six scenarios was provided to the model user along with a graphical means for defining the values in the sixth scenario, the latter being done independently for each river.

Precipitation

A similar analysis was again done to obtain "very dry", "dry", "typical", "wet", and "very wet" scenarios. Unlike levels and flows, however, precipitation was often zero, so was essentially missing on those occasions. Aggregation on the basis of cumulative distributions could not be employed, because that would have generated far too many zeroes. Instead the "typical" scenario was defined using mean values by day of the year, and the other scenarios defined by the 0.1, 0.5, 1.5, and 1.9 times the mean.

Section Backflows

The historical estimates of section backflow were used to parameterize the future period of the model as well. See above for a description of this parameter.

Tributary Phosphorus Input Concentrations

Future tributary input total phosphorus concentrations were represented for each river in the model as a constant value covering the entire future period. These are made accessible to the model user and can be altered independently by river from 0 to100 $\mu g\ L^{-1}$. The default values ($\mu g\ L^{-1}$) were: Trent River, 45; Moira River, 18; Salmon River, 15; Napanee River, 18; and Wilton Creek, 36 $\mu g\ L^{-1}$ These were based on averages of 2001 values from the budget work in Minns et al. (2004).

Atmospheric Phosphorus Input Concentrations

A constant value for total phosphorus concentration in precipitation was employed for both the historical and future periods. This parameter is described above.

Point Source Phosphorus Inputs

Point source inputs in the future were assumed to be entirely from STPs. These were parameterized in an external Microsoft Excel® workbook, containing separate specifications for the following STPs (Table 1). The effluent concentration and capacities represented the conditions for which each plant was certified to operate (R. Helliar, Ontario Ministry of the Environment, Kingston, pers. comm.). They implied a total STP load of approximately 27 kg total P per day should all plants be operating at 100 percent of capacity. The actual final effluent concentrations were often quite different from these at the end of the historical period, and implied a total load of less than 20 kg/day at design capacity. For the purposes of the model, however, each STP was assigned the values in Table 1 for every year in the historical period. The workbook calculated the loads and summed them by bay section to yield the numbers which were input to the model.

Gaming with the point source inputs was achieved simply by modifying the values of any of the three specification parameters for one or more STPs in any one or more years. To simulate addition of new STPs, three non-existent plants were included for each bay section (U1-U3, M1-M3, and L1-L3), all with their specification parameters set to 0. Modifying any one of the specification parameters effectively adds a new STP to the corresponding bay section.

Lake Ontario Phosphorus Concentration

A constant value is used for Lake Ontario total phosphorus concentration in the future. The default concentration is 8 $\mu g\ L^{-1}$, which was the average value in the last two years of the historical period. This parameter was also brought out to the user interface to allow variation between 0 and 50 $\mu g\ L^{-1}$.

MODEL PROCESSES

Water Budget

The hydrological budget was dealt with in essentially the manner described in Minns et al. (2004):

Outflow = River inflow (+ above section outflow) + Precipitation - Evaporation - Volume change

where the budget elements were parameterized as described above. Minns et al. (2004) estimated evaporation from a series of predictive equations published by Meredith (1975) which depended in part on air and water temperatures, and which were thus beyond the scope of this work. Evaporation was thus arbitrarily set equal to precipitation, allowing the latter to be included in the model for the purpose of defining the atmospheric phosphorus load. As noted above, volume change was computed as the product of a fixed (by bay section) surface area and daily water level change.

Section Phosphorus Budget

The basic water column phosphorus model is conceptually simple. Total phosphorus is added to a section water column store (P_W) via inflow from the tributaries, atmosphere, upstream section outflow, point sources, and reflux from the sediments. Phosphorus is removed from a section store via outflow to the next section and settling to the sediments. At any given time, the water budget defines a section volume which together with P_W yields a water column total

phosphorus concentration ([P_W]), which is the system's target variable. The initial value of each section P_W is determined by its initial volume (see above) and an initial [P_W] value, which was 70.4, 59.8, and 24.3 $\mu g\ L^{-1}$ for the upper, middle, and lower bays, respectively. These initial values came from the Minns et al. (2004) budget, and were simply the water column concentration for January, 1972.

Settling to, and reflux from, the sediments is discussed below. The other inputs and outputs were either the loads described above or computed as the product of a concentration times a flow, all of which are described above:

Quantity	Computed As
tributary input	tributary concentration times tributary flow
atmospheric input	Precipitation concentration times precipitation times section area
point source input	point source load
upstream input	upstream [P_W] times upstream section outflow
output via outflow	section [P_W] times section outflow

Section backflows are accounted for in this by creating additional inputs and outputs for the middle and lower bays which implement this scheme:

1. The middle bay backflow brings water into the middle bay having the [P_W] in the lower bay. An equal volume of water is displaced from the middle bay having the [P_W] in that section. A middle bay input and output are thus defined as the product of the respective concentrations and the backflow.
2. That in turn displaces an equal volume of water from the lower bay at the lower bay concentration, which is a lower bay output.
3. Finally the lower bay backflow brings water into the lower bay having the [P_W] in Lake Ontario, and an equal volume of water is displaced from the lower bay having the concentration in that section., thus defining the remaining lower bay input and output.

Sediment Processes

The portion of the model dealing with the sediments assumed a sediment mass defined by the product of the section accumulation area (defined in turn by the section area and accumulation extent) times a "sediment factor" (mass per unit area). The latter factor was taken to be a function of sediment thickness, sediment water content, and sediment solids density. The estimated sediment mass was then assumed to have a total phosphorus concentration ([P_S]), which thus defined a sediment phosphorus pool or store (P_S). The phosphorus in that pool was available for reflux to the water column and was also subject to burial, effectively removing it from the system.

The burial process was assumed to be defined by a fixed sediment concentration in the section tributary inputs, and from that a time-variant sediment load could be tied to the section hydrology. Parameter estimation for this was done by dividing an estimated sediment concentration of 0.0965 $g\ cm^{-2}\ year^{-1}$ (Minns 1986) by the average whole-bay tributary flow (1972 to 1977) and by 365, giving a "deposition constant" to be scaled to a daily deposition rate by multiplying by the summed daily section tributary flows. This scaled value was expressed as a loading rate (mass per unit area per day), and a deposition coefficient (per day) was computed by dividing that value by the sediment factor described above. The deposition coefficient thus defined the fraction of the sediment phosphorus store disappearing each day through the burial process. The effect of short-term variations in tributary flows was damped by applying Stella's

SMTH function to the burial process. The deposition constant described above was made alterable by bringing it out to the user through the model interface.

Phosphorus was added to the sediment pool via a settling process defined by a settling coefficient (per day) computed from the time-variant section mean depth (metres) and a settling rate constant (m day^{-1}). This gave the fraction of the current water column phosphorus store settling to the sediments.

The final process to consider was reflux from the sediment phosphorus store to the water column. Monthly historical estimates of this rate (kg day^{-1}) were available from the budget work of Minns et al. (2004). Their reflux estimates were those values which caused their monthly budgets to balance, i.e., they used reflux rates to force balancing. As such, then, their estimates could not be used directly in the model, because the model would then have been forced by its parameterization, rather than by independent input variables. Thus a means was required for predicting reflux rates given the state of the system at any given time.

The simple model described by Minns (1986), on which this Stella model was based, had reflux rates defined as a proportion of P_S. With this in mind, a boot-strap version of the Stella model was developed which was, in fact, forced by historical estimates of reflux, thus allowing comparisons between those rates and other sediment parameter values generated by the model. The historical rates involved were annual average rates from the Minns et al. (2004) budget work, applied within the period May through September only, rates in other months being arbitrarily set to zero. The resulting model output was used to generate annual mean P_S and annual mean $[P_S]$, which were plotted against the annual historical reflux rates to look for evidence of a relationship. Both plots were very similar in appearance, so attention was focused solely on the relationship involving $[P_S]$, because that should in theory be less subject to variations in other sediment model parameters such as thickness.

An exponential function was fitted to the shown data in Figure 3 for 1972 to 1995 using non-linear regression, with these results:

		95 % Conf. Limits	
Parameter	Value	Lower	Upper
a	0.015	-0.011	0.041
b	4.498	3.265	5.730
n	24		
r^2	0.7364		

So that:

$R = a(e^{b[Ps]})$, where R = reflux (mg m^{-2} d^{-1}) and $[P_s]$ = sediment P concentration (mg g^{-1}). In practice, the default values for 'a' and 'b' used in the model were 0.02 and 4.5, respectively, both made adjustable through the model's user interface. Reflux was again only non-zero in the summer months (May through September).

With regard to restricting reflux to the summer months, it should be noted that in early versions of the model this was not done. The result was that towards the end of the historical period, the annual variation of $[P_W]$ shifted from a pattern where it was essentially 180 degrees out of phase with the changes in tributary flows to a pattern where it was nearly in phase. This was manifested as a change from a pattern where concentrations rose and peaked every summer to one where they fell during the summer as flows declined. The observed concentration data employed by Minns et al. (2004) showed, however, that the latter pattern was not realistic, since concentrations always peak in the summer and do so in all bay sections. The restriction of reflux

to the summer months corrected this problem in the upper bay and reduced it in the middle and lower bays.

Finally, an adjustment for the reflux rates was developed to account for the trend in values seen in the post-1995 period (Figure 3), hypothesized to be due the effects of zebra mussels. A range of values for the parameter 'a' was developed which effectively translated the fitted curve up and down so as to pass through the range of observed post-1995 reflux rates. This "zebra mussel effect" ranged from 0.009 to 0.017 and was given a default value in the model of 0.01, again adjustable by the model user. The adjustment was applied simply by adding it to the model's 'a' value in all years after 1995.

The other sediment parameters were set based on the analysis presented by Minns (1986; Table 2). Of these values, only the accumulation extents were not made subject to change by the model user. The others were brought out to the user interface, with sediment thickness and initial [P_S] alterable by bay section, and changes in the remaining parameters applied to the whole bay.

MODEL OPERATION

Overview

After the "title page" (Figure 4A) for the model, the interface through which the user operates the model consists of a "home page" (Figure 4B) from which the model is actually run and most results are viewed, a results page (Figure 4C) showing mean [P_W] by year, and a "set-up page" (Figure 4D) which accesses several parameter pages (Figure 5) from which the user can alter some model parameters. These are described in more detail below.

Note that on first starting the application, a message will appear regarding the establishment of external links. This refers to the links to the external data used to parameterize future point source loads. The Microsoft Excel® workbook ("FuturePointSources.xls") containing those data must be open before a response is made to the message AND the response must be to click the "Yes" button.

Home Page

This is the main page from which the model is run and from which the user exits the system (Figure 4B). There are several features to note:

- a set of buttons in the upper left corner which allow the user to run, pause, and stop a simulation; as well there is a button which resets all parameters and outputs to their default states
- two buttons in the upper right corner: a home button, which just returns things to the same view, and an exit button for quitting a session and closing the application
- a "Set Up" button on the right side for bringing up the first of a number of set-up pages
- a "Mean Concs" button on the right side for bringing up the annual means page
- a "graph pad", which shows time series plots of all results other than the annual mean concentrations; clicking on the page-turner in the lower-left corner of the graph pad cycles through the available plots; the x-axis of all plots is given in days

To run a simulation, the run button in the upper left corner should be clicked. The cursor will change from a hand to a pointer, and the simulation will run, during which the

currently displayed graph will be redisplayed. The simulation is complete when the cursor is restored to its normal state, at which time various plots may be viewed in the graph pad or annual and summer mean [P_W] values may be viewed by clicking on the "Mean Concs" button. The six available plots are:

- a separate plot for each bay section showing the model [P_W] ($\mu g\ L^{-1}$) along with the summer mean [P_W] values obtained by Minns et al. (2004)
- a plot showing the model P_S (kg) for all sections
- a plot showing section point source loads (kg day^{-1}) for all sections
- a plot showing reflux rates for all sections (kg day^{-1})

Means Page

The means page (Figure 4C) has a single "table pad" with just two tables, one showing annual mean [P_W] by year for all three bay sections, and the other showing summer mean [P_W]. The upper right corner has a home button returning the view to the home page and a "back" button returning the view to the previous page (which in this case should be the home page as well).

Clicking on the table pad's page-turner toggles between the two tables. Columns of results may be selected in the table by clicking on them or by pressing control-A to select all columns. The results may then be copied to the clipboard by pressing control-C, from which they may be pasted into other applications.

Parameters Pages

Clicking on the "Set Up" button on the home page brings up a switchboard page (Figure 4D) with buttons to bring up set-up pages for adjusting parameters related to phosphorus input, the sediment model, hydrology, and point-source inputs:

Each set-up page (Figure 5) has buttons for returning to the home page and for returning to the previous page. In terms of set-up, the point-source page simply bears a message reminding the user about the external source of the point source parameters used in the future period of the model. The other pages allow changing of model parameters and bear three different types of input devices:

- slider controls – clicking on the slider button and dragging it causes the parameter value to change continuously
- radio knobs – clicking on the knob and dragging in a circular path causes the knob to rotate and changes the associated parameter value continuously
- graphical input devices – double-clicking on the graph opens a dialog, clicking within the graph portion of the dialog changes the parameter value as a function of time

Each has a small button labelled with a question mark. Clicking on it will bring up the internal documentation related to the associated model parameter, which will describe that parameter and explain the basis for its default value. If a parameter is altered through one of these devices, a second small button labelled with a "U" will appear to indicate that fact. Clicking on it will restore the device to its default state.

The phosphorus input page (Figure 5A) has nothing but sliders, used to control future tributary phosphorus concentrations by river, the future precipitation phosphorus concentration, and the future concentration in the outlet basin of Lake Ontario. The defaults are described above in the discussion about future parameterization.

The sediment model page (Figure 5B) has sliders for setting the sediment thickness by section and initial [P_S] by section. Also modifiable are the sediment properties parameters (solids density and water content) and sediment process parameters (settling rate and deposition constant). These are all described above and it is recommended that these remain at default values.

Three radio knobs are linked to the reflux model. Two alter the values of 'a' and 'b' in the exponential relationship which gives reflux rates from [P_S]. These too should probably not be changed. The last radio knob adjusts the zebra mussel effect between zero and the maximum value as described above in the description of the sediment model. This adjustment is intended as a gaming tool.

The hydrology page (Figure 5C) has three radio knobs, each with values of 0, 1, 2, 3, 4, and 5 for independently selecting one of 6 future scenarios for tributary flows, water levels, and precipitation. Changing the value of a knob from 0 through 4 selects scenarios varying from very low to very high. Setting a knob at 5 selects a user-defined scenario. The latter is implemented via associated graphical input devices (as described under "Parameters Pages", above) which allow the definition of an annual pattern of water levels, precipitation, or flows by river. Two other graphical input devices allow the user to change the annual pattern of backflows, affecting both the historical and future periods.

The point source page (Figure 5D) has summary guidance on the use of the external Excel spreadsheet to devise future point source loading scenarios.

RESULTS

BASELINE SIMULATIONS

Once the model parameters were set for the 1972-2001 period and hydrologic scenario options set for 2002-2031 a baseline simulation was run. The baseline scenarios made the following assumptions for the period 2002 onwards: a) hydrology would follow the median flow cycle (50^{th} percentile of 1972-2001 daily flows), b) median zebra mussel effect on sediment reflux rates based on the rates estimated in the 1996-2001 period, and c) point-source effluent flows would continue at 2001 levels with the Certificate of Approval (CoA) concentration of 300 $\mu g\ L^{-1}$. The daily graphs from the STELLA model show the seasonal cycles of phosphorus concentration in the upper, middle and lower bay section water column and surface sediment (Figure 6). The movement to steady state in the surface sediment [P] continues throughout the simulation period, 1972-2031. The water column values appear to come close to steady state soon after 2001 although the continuing changes in the surface sediment will go on causing small changes. The summary graphs of mean summer [P] in the water column provide a smoother picture of longer term trends (Figure 7). The results show that the recovery process is expected to continue after 2001 as long as 2001 STP flows continue at CoA concentrations. By 2031 the water concentrations are close to steady state, within 0.2 $\mu g\ L^{-1}$ of their final value.

ALTERNATE SCENARIOS

Hydrologic Effects

The hydrology scenarios used to project future conditions in the Bay of Quinte were based on percentiles of daily flow in the period 1972-2001. The 10, 25, 50, 75, and 90^{th} percentiles of flows that occurred 1972-2001 were taken to represent very dry, dry, median, wet, and very wet conditions respectively. With point source loading set at 2001 levels and zebra mussel effects at median levels, the model predicts that under both the "dry" and "very dry"

scenarios, mean summer upper bay [P] will rise in the future taking conditions back along the path to eutrophication (Figure 8). At median and higher flow rates the summer concentrations trended to lower levels. The rise comes about because at lower river flows, turnover of the surface sediment layer slows down thereby allowing sedimented phosphorus to accumulate as in the past and increase regeneration rates. As Quinte river flows have shown a tendency toward lower levels in the latter half of the period 1972-2001 (Minns et al. 2004) it would be wise to base future point source loading limits on dry conditions. On that basis, 2001 loads, which were the lowest in the 30 year record, may be too high.

While predicted mean summer [P] declines in the upper bay as flow levels are set higher, the opposite occurs in the middle and lower bay sections (Figure 9). Increased throughput from the upper bay due to higher flows out-competes the back-flows from Lake Ontario thereby leading to slightly higher concentrations; a result that may not have been immediately obvious without the benefit of this predictive model.

"Zebra Mussel" Effects

In the baseline model, the "zebra mussel" parameter affecting sediment P reflux was set at the midpoint of the values estimated for each year after 1995. Dreissenid mussel biomass increased significantly over the period from 1995 to 2000 after the initial invasion (R.D. Dermott GLLFAS, Burlington, pers. comm.). The increase in reflux rates is attributed to zebra mussels for convenience but may also involve macrophytes which also increased significantly (Seifried 2002). Predicted mean summer [P] in the upper bay increased in the upper bay after 1994, as demonstrated in budget calculations (Minns et al. 2004). To examine how zebra mussel abundance might affect future in-bay [P]s, the model was run with a range of zebra mussel (ZM) coefficients (0, 50, 100, 150, and 200 percent of the baseline value). Higher ZM coefficients lead to higher summer mean upper bay concentrations (Figure 10) with the effect being damped somewhat over time as the sediment P pool comes into steady state with the increased reflux rates. In 2031 it is predicted that the highest zebra mussel effect would produce a summer mean 7 $\mu g\ L^{-1}$ higher in the upper bay and 2 and 0.4 $\mu g\ L^{-1}$ higher in the middle and lower bay sections, respectively (Figure 11).

The likely future abundances of dreissenid mussels and of submerged macrophytes may differ from those attained in 2000. It is therefore prudent to assume a continued effect on future reflux rates, and accordingly, it is recommended that the median 1995-2001 value be used for assessing other changes.

Point Source Load Expansion

In 2001 none of the sewage treatment plants (STPs) releasing effluent into the Bay of Quinte were operating at 100 % flow capacity and most were achieving final effluent concentrations below the 300 $\mu g\ L^{-1}$ specified in their Certificates of Approval (CoA). As the lower tributary flow scenarios had already shown future increases in upper bay [P] at 2001 loading levels, additional scenarios were run to examine the interaction between tributary flow levels (LF and MF, 25 and 50 percentile levels) and future 100 percent flows at all STPs starting in 2010. At median tributary flows the model predicts that future mean summer upper bay [P] would be at most 1 $\mu g\ L^{-1}$ higher (Figure 12). However, at low flows, both the current efficiency (CEF) as seen in 2001 and CoA scenarios lead to much higher concentrations (Figure 12). There is little response in the middle and lower bay sections (Figure 13). By 2031, the low flow would produce upper bay concentrations 9.2 and 13.1 $\mu g\ L^{-1}$ higher than the baseline scenario, CEF and

approved CoA, respectively. Because these values are well above the interim RAP targets, it is clear that currently approved final effluent concentrations will have to decrease before the Quinte STPs reach maximum flow capacity.

As the predictions of future conditions indicate a risk of a recurrence of higher mean summer upper bay [P] values it is important to consider setting a point source load limit for the upper Bay of Quinte. It is reasonable to assume that the zebra mussel effect will continue at median levels in the future and that river flows will most likely occur in the range bounded by the low (25%) and median (50%) levels. A load limit reference criterion is therefore needed. The original interim target for the upper bay in the summer was 30 $\mu g\ L^{-1}$, but it is evident that this target is unlikely to be met because the mean tributary inflow [P] lies above that value and the zebra mussel effect generates still higher values. Instead, the period 1990-2001 might be considered a reference period when point source loadings were generally low. If the whole period is taken, the average (N=12) mean summer upper bay [P] was 36.1 $\mu g\ L^{-1}$ with a std. dev. of 5.83 and a 95% confidence interval of ± 3.3 $\mu g\ L^{-1}$. The upper confidence bound (39.4 $\mu g\ L^{-1}$) might be used as a reference point for the future. However, half this series occurs before zebra mussels arrived with their associated raising of in-bay [P]. If the 1996-2001 period is taken, the average (N=6) mean summer upper bay [P] was 38.0 $\mu g\ L^{-1}$ with a st.dev. of 6.59 $\mu g\ L^{-1}$ and a 95% confidence interval of ± 5.3 $\mu g\ L^{-1}$. The upper confidence bound (43.3 $\mu g\ L^{-1}$) can be used as a reference point for the future. If predictions out to 2031 at low and median flows are taken to define an expected future range of upper bay [P] values, the percentage of that range that lies below the boundary target can be taken as a measure of how secure the bay's water quality might be.

To examine a range of options, using 2010 as a common starting point for implementation of changes, alternate STP flow and effluent concentration combinations were examined. As all STPs are currently operating below 75 percent maximum flow capacity as per their CoAs, resetting maximum flows at 75 and 80 percent of capacity with 300 $\mu g\ L^{-1}$ concentrations was examined. Alternately, as the combined average effluent concentration was 177 $\mu g\ L^{-1}$ in 2001, a range of effluent concentrations (250, 200, 150) was examined assuming 100 percent flow capacity. Only one of these combinations produced results better than the baseline condition, 100 percent flow capacity with 150 $\mu g\ L^{-1}$ (Table 3). A continuation of the circa 2001 flow and concentration levels produced the best outcome with 97 percent of the range being under the limit. An upper bay load limit in the 15-20 kg day^{-1} range would ensure that 75-80 percent of the future in-bay concentration range would lie below the target of 43.3 $\mu g\ L^{-1}$. Such a target is not an immediate requirement as the predicted conditions do not occur until 2031. If river flows show a further tendency toward lower levels, the load limit would have to be set at the lower bound or even below. Current point-sources flows and effluent concentrations are mostly below that limit giving the municipalities time to plan for the next stage in the evolution of STP facilities to protect water quality in the Bay of Quinte. Small increments of loading in the short-term should not pose any immediate threat to the Bay. In the long-term, given population growth and associated utilization of STP capacity coupled with likely lower rivers flows in response to climate change, implementation of a more stringent local point source P loading limit for the upper bay will be necessary to protect the water quality gains obtained through past efforts, 1972-2001.

Point versus Diffuse Source Control

In recent years diffuse source phosphorus controls have gained greater attention with an expectation of building on the success of point source controls. There may also be a perception among many observers that further gains in water quality improvement are not highly cost-effective. Unfortunately, among those advocating further non-point source controls, there has been a tendency to focus on absolute loading rates which can be misleading when examining the benefits of phosphorus control in the receiving water body. In the Bay of Quinte, this is a particular problem since the drainage area is so large and tributary, or non-point source absolute loadings are large compared to the direct point sources. In the 1972-2001 period, annual and summer tributary loadings averaged 660.3±64.4 (95% confidence interval) and 373.6±62.7 kg day^{-1}, respectively (Minns et al. 2004). The average annual and summer tributary [P]s were 35.1±2.2 and 36.0±2.2 μg L^{-1}, respectively. On average a 1 μg L^{-1} decrease would have decreased loading by 18.8±1.3 kg day^{-1} annually and 10.4±1.5 kg day^{-1} in summer. Trent River flows and P loadings dominate inputs to the Bay of Quinte and analyses of the 1972-2001 budgets indicated no measurable change in the mean [P] on an annual basis over that 30 year span (Minns et al. 2004). Hence, it is not reasonable to expect any significant change in the future. Nonetheless, the model can be used to explore the possibilities.

In the baseline model, a mean Trent River [P] of 45 μg L^{-1} is used. Simulations were run using values of 44 and 43 with both median and low flows (Table 4). The scenarios show, not unexpectedly, that a 1 μg L^{-1} decrease in tributary concentration produces approximately the same result in the mean summer upper bay value. If it is assumed that all STPs run at 100% flow capacity with 300 μg L^{-1} from 2010, similar results are obtained. A 2 μg L^{-1} concentration decrease in the Trent River can offset the effect of the on-bay STPs using 100 percent of their capacity. As there is no evidence to indicate that such a tributary decrease is achievable, however, it would be unwise to assume loadings are interchangeable. While there are no doubt local benefits to be obtained within watersheds where phosphorus, and sediment exports can be decreased, the ability to realize those benefits in receiving waters are lessened as distance to outlet increases. Achieving a 2 μg L^{-1} reduction across the whole of the Trent River drainage of 12549 km^2, or, for that matter, the whole Bay of Quinte drainage (18182 $km^{2)}$, is unlikely and would not be cost effective compared with direct on-bay load reduction investments at sewage treatment plants.

DISCUSSION

MODEL PERFORMANCE

Goodness of Fit

The phosphorus model used here is a modified version of Minns' (1986) and is consistent with other phenomenological phosphorus models including Vollenweider (1969), Lorenzen et al (1976) and Chapra and Canale (1991). In shallow lakes, sediment P pools play a greater role in determining P concentrations in the water column and cause response lags when external inputs are reduced. Beyond the basic elements of input-output for the water column and surface sediment pool there is no attempt to develop or imply any of the many cause-effect mechanisms undoubtedly at work in ecosystems. The fitting of phenomenological models is driven by observation and we were fortunate here to have a 30-year record to draw on spanning a wide range of external loading levels.

Of necessity the model calibration centred on agreement between observed and predicted mean summer water column [P] in the three bay sections as this is the best data available. In the

nutrient budget analyses winter in-bay [P] values have to be estimated for the most part by interpolation between end of summer and spring values, supplemented to some extent with water intake measurements. Hence the budget-based annual means are a less reliable source for calibration; either or both of the interpolations or the predictions could be inaccurate. The advantage of the model is that it implements a consistent mass-balance scheme bounded by measured tributary flows and estimated Lake Ontario back-flows. The model is consistent with the budget analyses in that much of the uncertainty is channelled into the reflux rate estimates. Nonetheless, the estimated reflux rates are consistent with literature values, particularly in the upper bay where back-flow induced errors are absent. The sediment characteristics were adjusted slightly from the approach used by Minns (1986) in the steady-state modelling.

The serial sediment budgeting that allows a relationship between estimated reflux and surface sediment [P] to be established is subject to a number of unknowns in the sediment pool but is constrained insofar as much faster or much slower sediment pool turnover rates would make it harder to obtain a good fit with the water column calibrations.

Phosphorus Reflux and the 'Zebra Mussel Effect"

The process of setting parameter values in the model and calibrating against observed values for the 1972 to 2001 period led to two modifications of the Minns (1986) model. First, in the original model sediment P reflux was expressed as a proportion of the total surface sediment pool. This approach made it impossible to get a good model fit of the whole 30 year calibration period. Changing to an areal rate controlled by the surface sediment [P] produced much better results. The exponential form of the equation also makes sense given that some aspects of sediment-water nutrient exchange are surface-related. This empirical model makes no inferences about the mechanism(s) of sediment P reflux. There are likely a number of processes contributing to overall reflux, including: decomposition of recently (current season) sedimented algal material; diffusion of P between interstitial water and the overlying water column; wind and turbulence driven resuspension of sediments that bring P back into the water column, bioturbation by benthic organisms such as chironomids, oligochaetes, molluscs, etc.; and root-extraction of nutrients by macrophytes that lose excess P into the water column or release it via decomposition (e.g., Istvanovics 1988; Barko and Smart 1980). These mechanisms are modified by organic enrichment which alters redox conditions and by temperature, both of which alter the availability of P in the surface sediment layer and the overlying water (Uhlmann and Guderitz 1988; Nicholls 1999). In the model it is assumed that reflux only occurs in the May to October period on the basis that it is in that period that temperatures are higher, biological processes more active, and the waters open to recirculation. In the winter, ice-cover prevents resuspension. Higher surface sediment [P] is generally indicative of greater enrichment and higher reflux rates are expected.

The second modification, "the zebra mussel effect", was again dictated by the calibration process. Assuming the same reflux rates prevailed after the colonization of dreissenid mussels (DMs) and the associated changes led to water column [P] being under-predicted. The serial analysis of the sediment pool budget also indicated an increasing effect since the arrival of the DMs. This is consistent with the large increases in DM biomass over the 1995 to 2000 period (Ron Dermott, DFO GLLFAS, Burlington, pers. Comm.). The reflux model modification does not imply any particular mechanism; however, there are two key possibilities: 1) dreissenid mussels intercept more P by filtration and much is readily returned to the water column either by ready decomposition of their pseudo-faeces or by excretion; and 2) increases in macrophyte and

epiphyte biomasses as the DMs increased water clarity have resulted in more P being taken up via root systems and excreted or released by decomposition into the water column. The budget and model analyses do not allow the exact mechanism(s) to be determined, but the model building process leads to the generation of testable hypotheses.

The "zebra mussel" effect in this model, and in the budget analyses for 1996-2001, indicates increased [P] values in the water column. This differs from results reported elsewhere in the Great Lakes. Mellina et al. (1995) indicated that the colonization by zebra mussels did not alter [P] levels in western Lake Erie, Lake St. Clair and Oneida Lake. Nicholls et al. (1999) reported that at several water intakes on the north shore of Lake Erie [P] levels did decline after dreissenids invaded. In the Quinte model, the increased [P] result is evident in all sections of the bay but most pronounced in the shallow upper bay. The much higher throughput rates for water and P in the Bay of Quinte compared to inshore sites and less flushed lakes might provide some explanation of the different responses. In general, the model predictions are consistent with long term observations and the findings of Project Quinte; upper bay [P]s in water were trending lower in the early 1990s before dreissenids arrived and have been consistently higher since (Minns et al. 2004).

While there has been a tendency to focus on the dreissenids themselves as the source of changes in lakes (Mellina et al. 1995), other conditions have changed, notably in the macrophyte community in the Bay of Quinte. Macrophytes mobilize P from sediments (Barko and Smart 1980). Also, summer water temperatures post 1994 have been higher than in the previous decade. Nicholls (1999) showed a dramatic effect of water temperature of sediment P release rates for the upper Bay of Quinte. From a P budget and model perspective, it is the net effect that is important in determining future likely outcomes. Delineation of cause-effect mechanisms will require further work.

Behaviour

The Quinte P model's responses are determined by two main inputs (runoff, point-source loading) and two internal mechanisms (the differential turnover times of water and sediment pools, and the "zebra mussel effect" on reflux rates). The pool turnover times are linked to the runoff while the point-source loadings are linked to the sediment P pools and hence the reflux rates.

The lagged response of the model to changed conditions highlights the contrast between the fast components, the water columns, and the slow components, the surface sediments. The high throughput of water and nutrients arising from both the runoff from the large drainage area and the back-flows from Lake Ontario (Freeman and Prinsenberg 1986) tends to create an expectation of almost instantaneous response to changes in loadings. However, the long turnover times of the surface sediment layers result in delayed steady state outcomes as observed by Chapra and Canale (1991) and others. Changes in runoff alter the rate of arrival of new sediment that leads to the turnover in the surface sediment layer. Thus, lower runoff lengthens the sediment turnover time and can lead to P enrichment as long as point source inputs continue. The point-source inputs remain an important contributor to elevated in situ [P] levels during the summer even at low loading levels. The "zebra mussel" effect further complicates the situation by increasing water [P] levels in summer and decreasing retention.

CONCLUSIONS

- The modified Minns (1986) model provides a good empirical fit to events seen from 1972 to 2001 in the Bay of Quinte. The phenomena modelled in the bay are similar to those modelled in other shallow waters and produce similar outcomes.
- The establishment of dreissenid mussels in the Bay of Quinte and associated changes (including increased water clarity that contributed to expansion of macrophytes), as well as elevated summer water temperatures of recent years, have altered P dynamics such that water concentrations are higher than expected from prior budget analyses. Since dreissenids are expected to continue to play a continuing role in the future, their presence must be factored into P management plans.
- Lower flushing rates in the latter part of the observational period and the effect they have on in-bay P concentrations sets bounds on future P management. For modelling purposes, point source P loading limits should assume that river flows below past median levels are more likely in the future as a safety precaution.
- Projections of future bay conditions with the current P load limit, constrained by dryer hydrology, higher summer water temperatures and the presence of dreissenids indicate the current limit is too high if the level of restoration of the Bay of Quinte, achieved through past efforts, is to be secured for the long-term. The analyses do, however, suggest that there is a reasonable time window available in which to plan for lower load limits and that small interim increases in the transitional period will not pose a serious threat.
- Comparisons of point versus diffuse load controls indicate that to a limited extent some load reduction trading is theoretically possible but is likely to be impractical in most cases given the high flows associated with most non-point sources. Phosphorus concentrations in the Trent River, for example, have not declined in recent years. The Trent River is the dominant diffuse source and to achieve reductions of only 1 or 2 $\mu g\ L^{-1}$ in its mean concentration would require a uniformly successful land management program over a drainage area of > 12,000 km^2. This may not be cost effective compared to further point source control around the Bay. Further, as Johnson and Owen (1971) demonstrated for the Bay of Quinte, net loading calculations which adjust total loads for hydraulic displacement effects will continue to show point source loadings are the primary cause of eutrophication. However, this conclusion for the Bay should not be interpreted as a reason to lessen efforts to reduce point, e.g., STPs, and non-point, i.e., agricultural releases, nutrient inputs upstream in the drainage basin; the water quality benefits of control and prevention, and the costs of inaction and neglect, usually lay close to the sources.

RECOMMENDATIONS

To evaluate the performance of the model in the future, there are several steps that are necessary:

- The current phosphorus concentration in the surface sediments of the Bay of Quinte should be reassessed. The model predicts that substantial changes have occurred since the 1970s and hence new values would provide a critical test of the model. Sources of previously published and unpublished data should be examined for their potential to serve as background data for a contemporary sampling of the Bay of Quinte sediments.
- The point source and tributary flows and concentrations should be monitored more rigorously to allow updated estimates of water flushing and P loadings. The mean in-bay summer

concentration of P in the water column of the three bay sections provide the most direct measure of the continued predictive power of the model.

- To manage phosphorus loading into the Bay of Quinte in the future, and thereby protect the restoration already achieved, several steps are necessary
    - Point-source loading directly into the Bay of Quinte needs to be managed on a watershed basis rather than at the level of the individual municipality. The loading into the upper bay (above the confluence with Hay Bay) requires the most attention.
    - The Ontario Ministry of Environment and the Bay of Quinte Restoration Council should establish a loading limit of 15 kg P day^{-1} for all the point sources in the upper Bay and then make allocations to specific communities from that limit on an equitable basis with all parties sharing in the costs and benefits of meeting the load limit. [As current loads are below capacity, some time (5 to 10 years) is available to develop and implement an acceptable approach.]
    - The Ministry of the Environment and the Bay of Quinte Restoration Council should keep the model up-to-date and use the model to assess the impact of any additional discharges from new potential point sources. [This action will require that monitoring of the necessary elements for water and nutrient budgets calculations be improved over current circumstances and maintained (cf Minns et al. 2004).]
    - There should be no consideration for using the middle and lower bay sections as recipients of future loading increases though they appear to be less sensitive as a result of back-flows from Lake Ontario. The middle and lower bay sections are vulnerable to hypolimnetic oxygen depletion (Minns and Johnson 1986)..
    - Area load limits need to be considered in all jurisdictions around the Great Lakes because current management schemes based on concentration limits will not prevent the reoccurrence of eutrophication as populations grow and additional STPs are built.

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Figure 1. STELLA flow diagram for Bay of Quinte phosphorus model. Black boxes are the water and sediment P stores for the three bay sections.

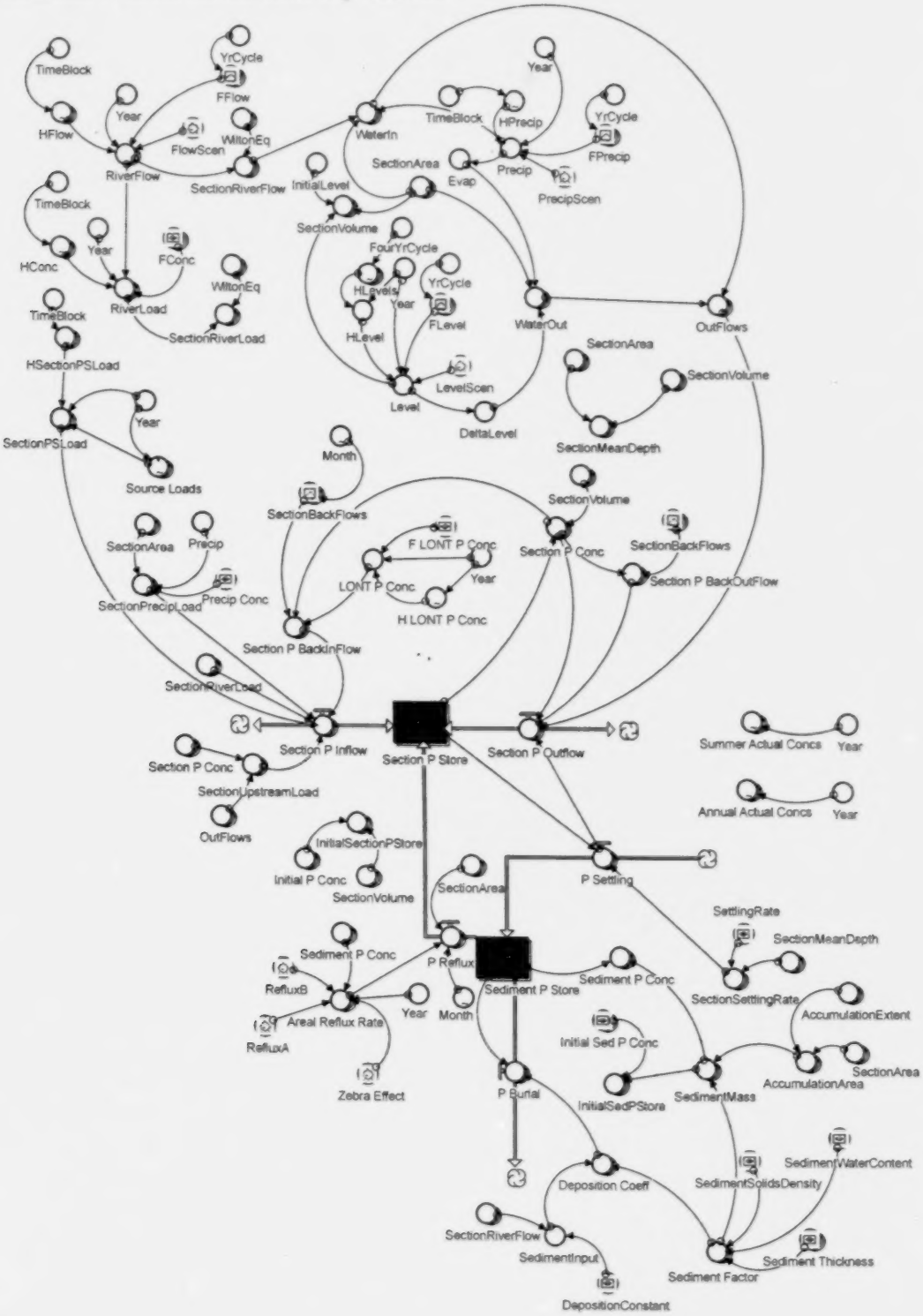


Figure 2. STELLA diagram of user and time base control blocks and the annual and summer average computation of the Bay of Quinte phosphorus model.

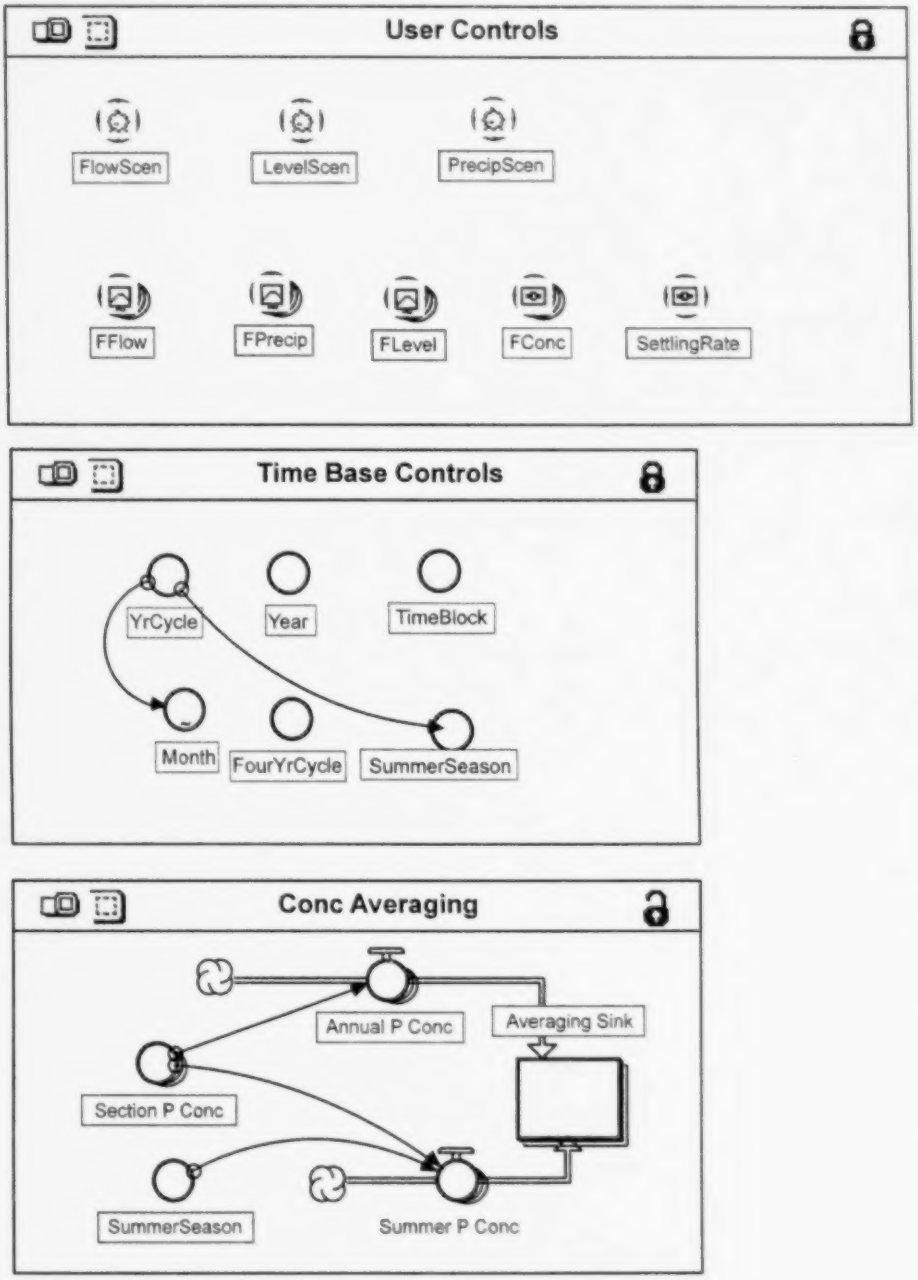


Figure 3. Estimates of annual reflux rates as a function of sediment P concentration. The solid line is the fitted exponential function, Reflux = $0.015e^{(4.498*[Ps])}$.

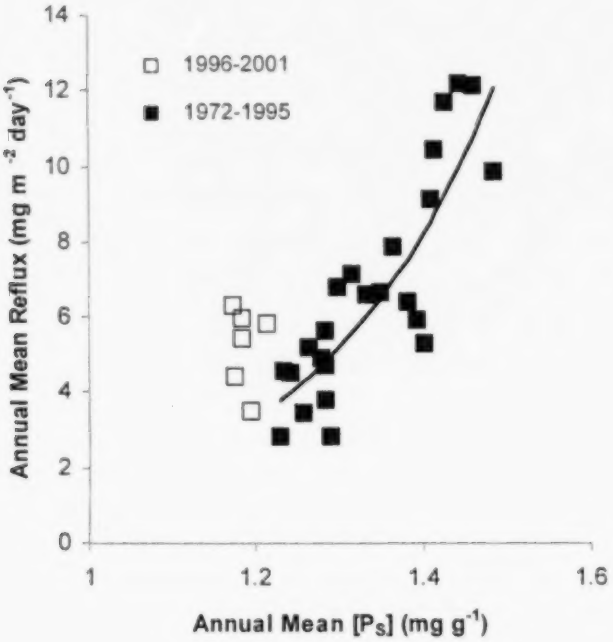
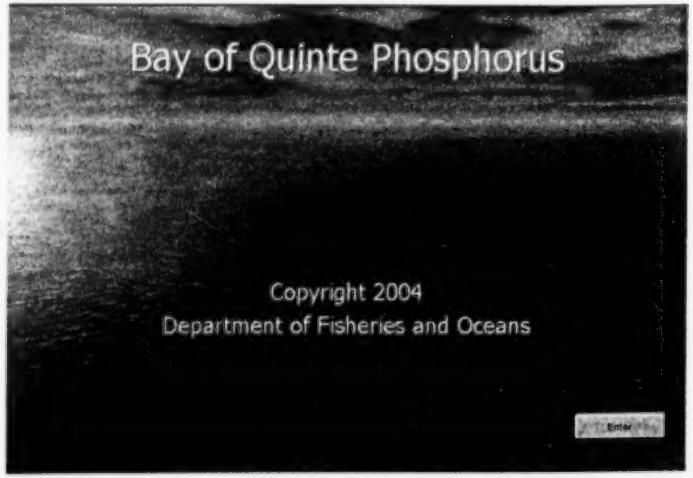


Figure 4. Display screens in the STELLA Bay of Quinte phosphorus model: A) Opening screen in run-time version, B) Graphical output screen, C) Mean annual and summer [Pw] screen, and D) Model set-up switchboard screen.

A)



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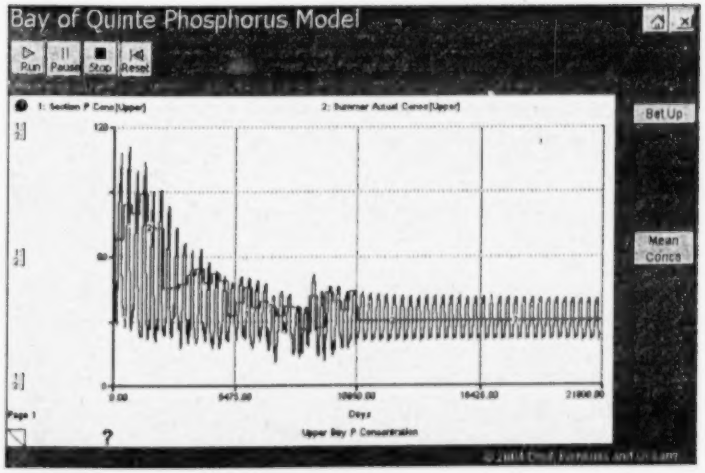
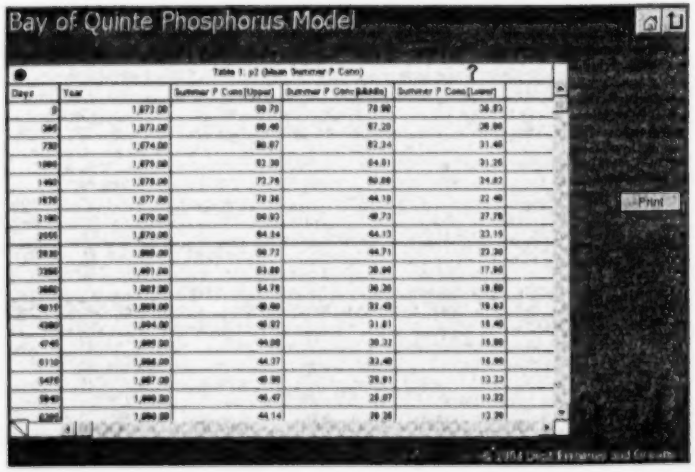


C)



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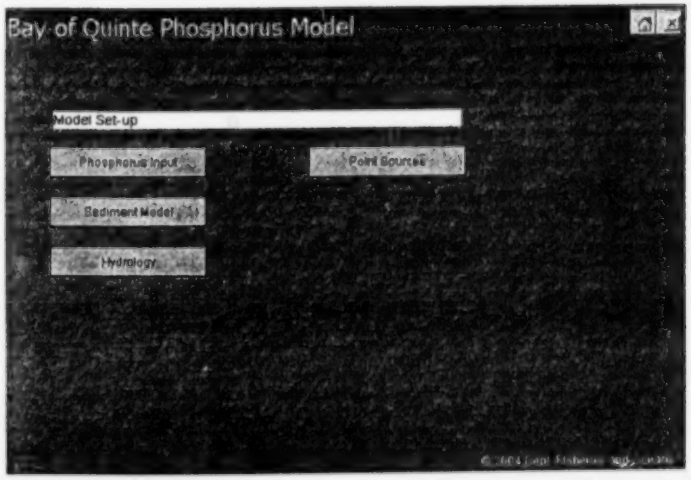

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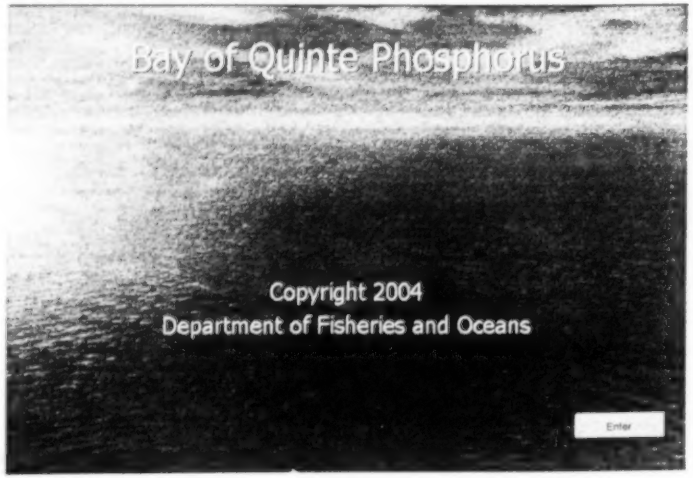

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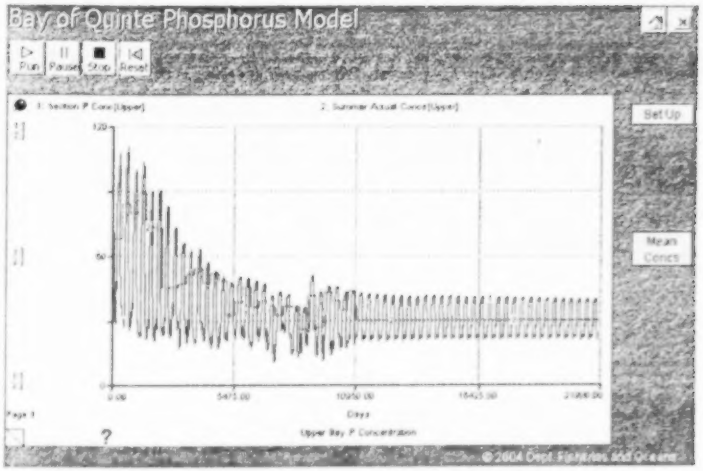

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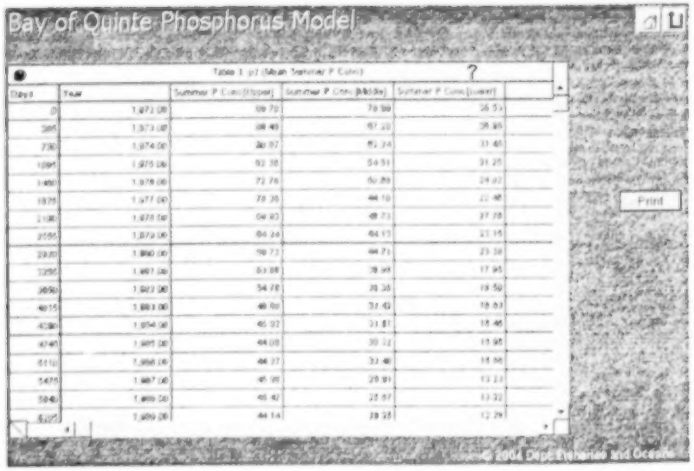

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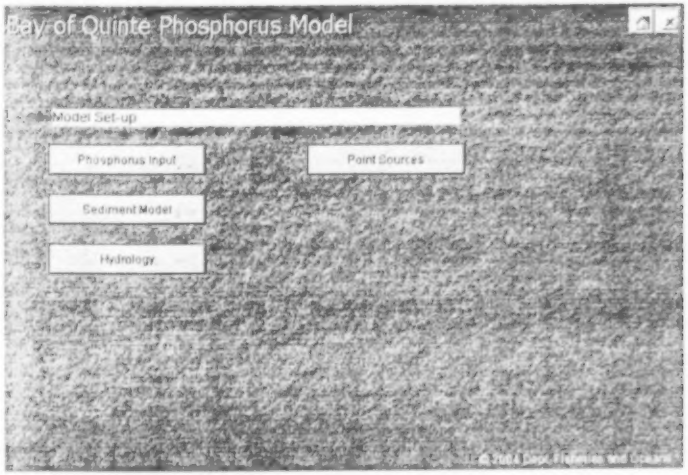
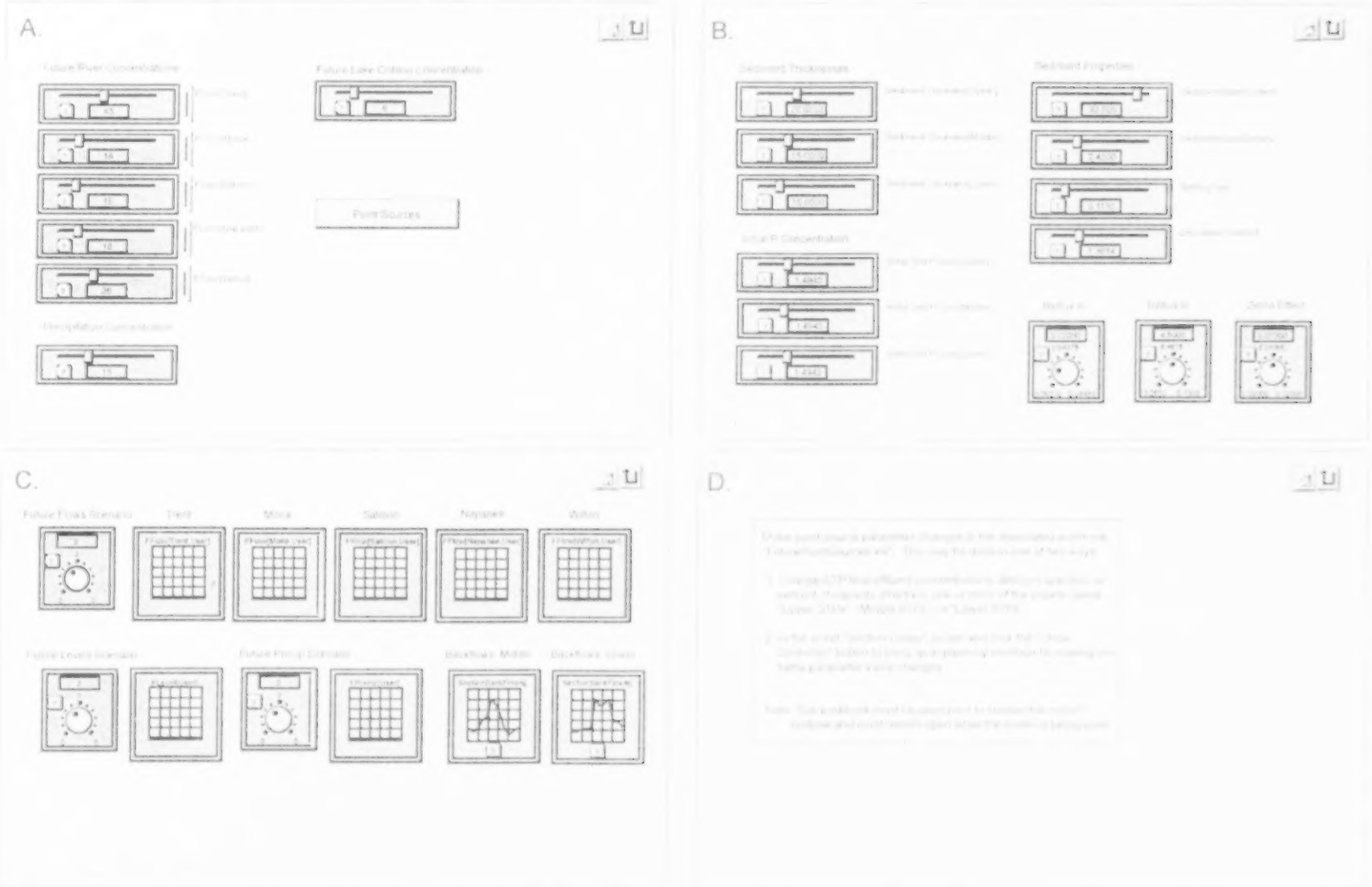


Figure 5. Control panels for designing future scenarios in the STELLA Bay of Quinte phosphorus model. A) Nutrient concentrations in tributaries and precipitation plus a link to point source scenarios in an Excel spreadsheet, B) Sediment properties and phosphorus reflux parameters, C) river flow, precipitation and water levels, and D) directions to the point-source scenarios in Excel.



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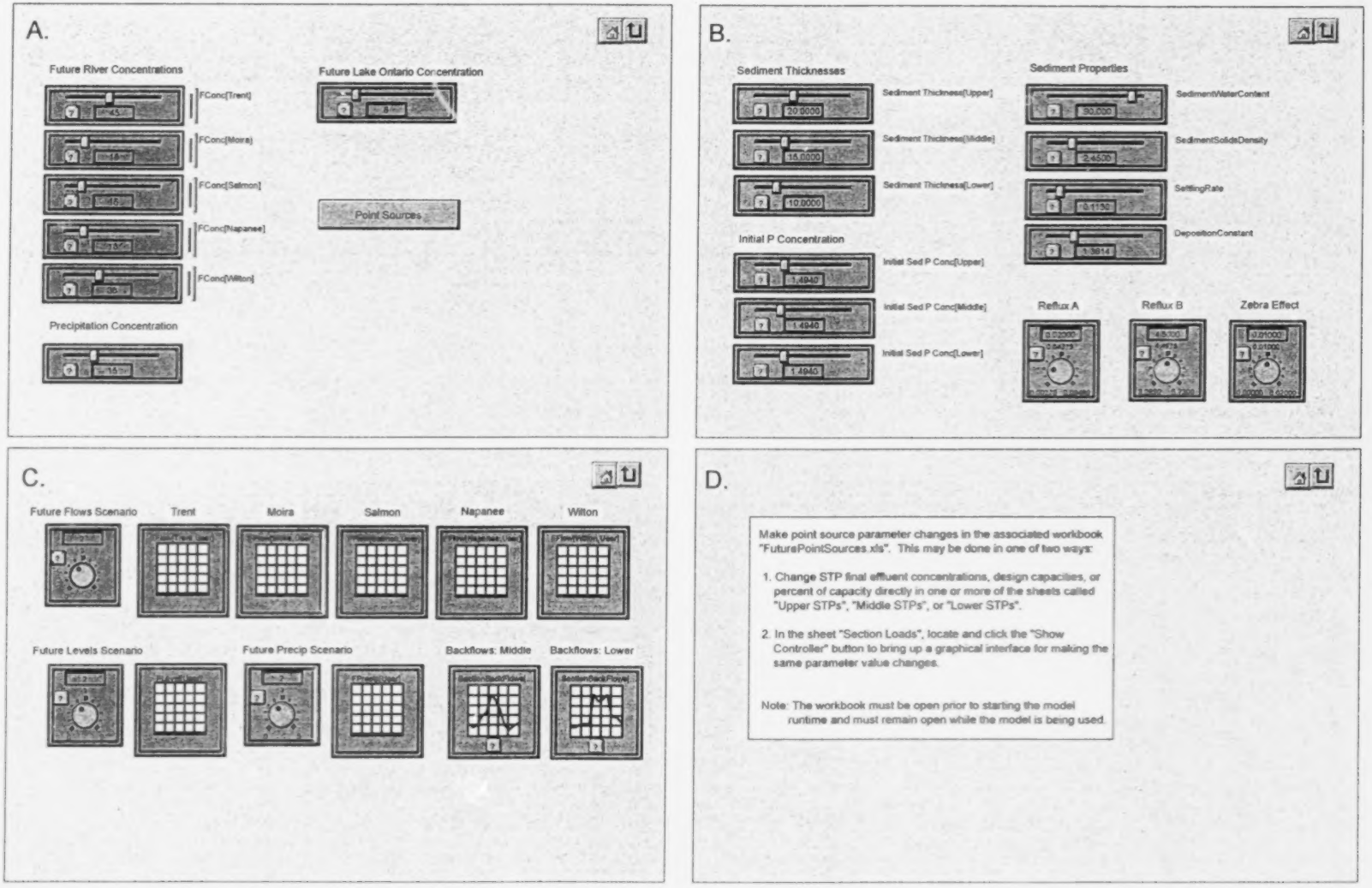
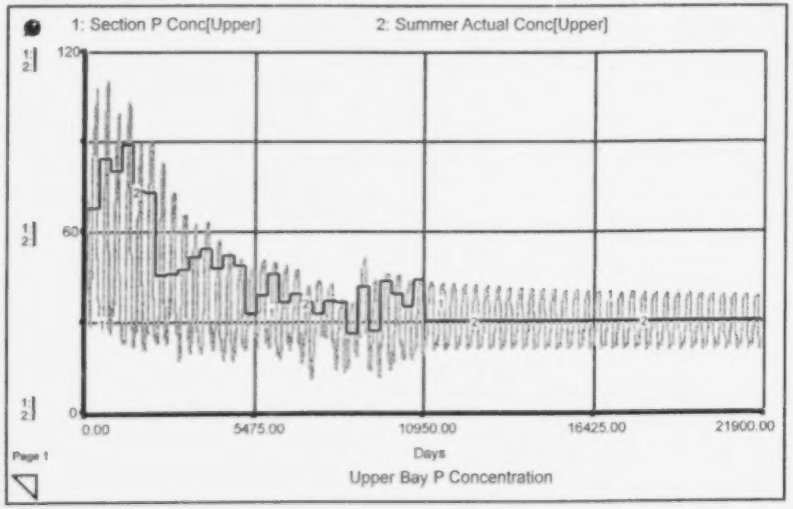
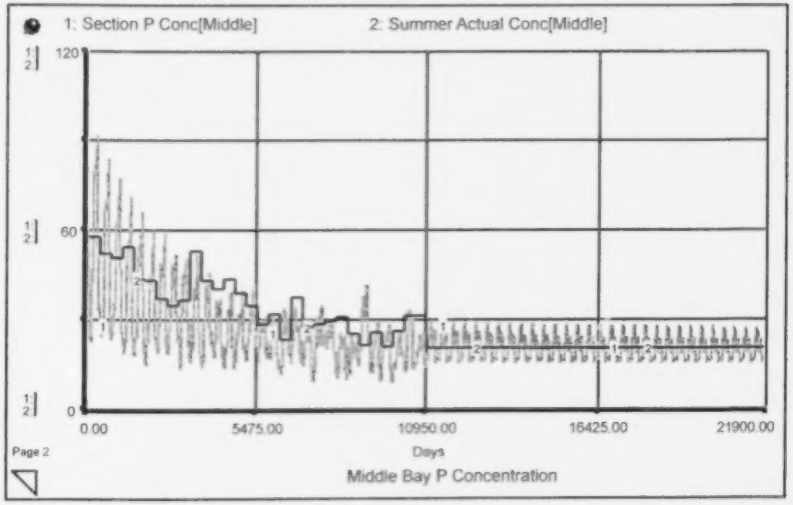
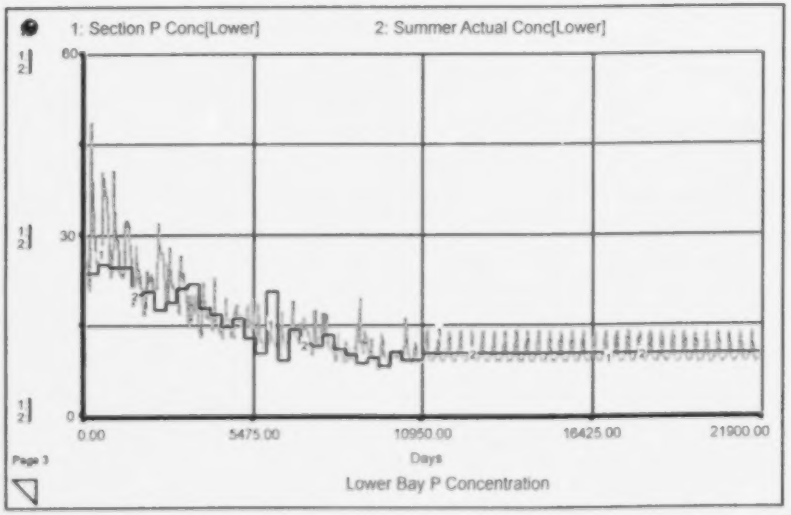


Figure 6 Graphs adapted from the STELLA display output in the Bay of Quinte phosphorus model showing the daily phosphorus concentrations in the water column and surface sediment in the three Bay of Quinte sections, upper, middle and lower.[The time axis is in days from January 1, 1972, to December 31, 2031. The water column values appear to come close to steady state soon after 2001 (day 10950).]







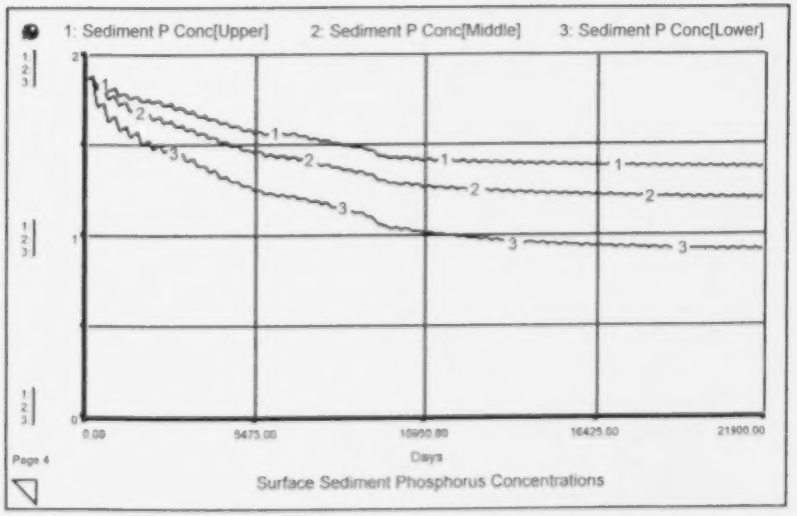


Figure 7. Baseline predictions of A) annual and B) summer mean phosphorus concentrations (μg L^{-1}) in the upper, middle, and lower sections of the Bay of Quinte, 1972-2031 (see also caption to Figure 6).

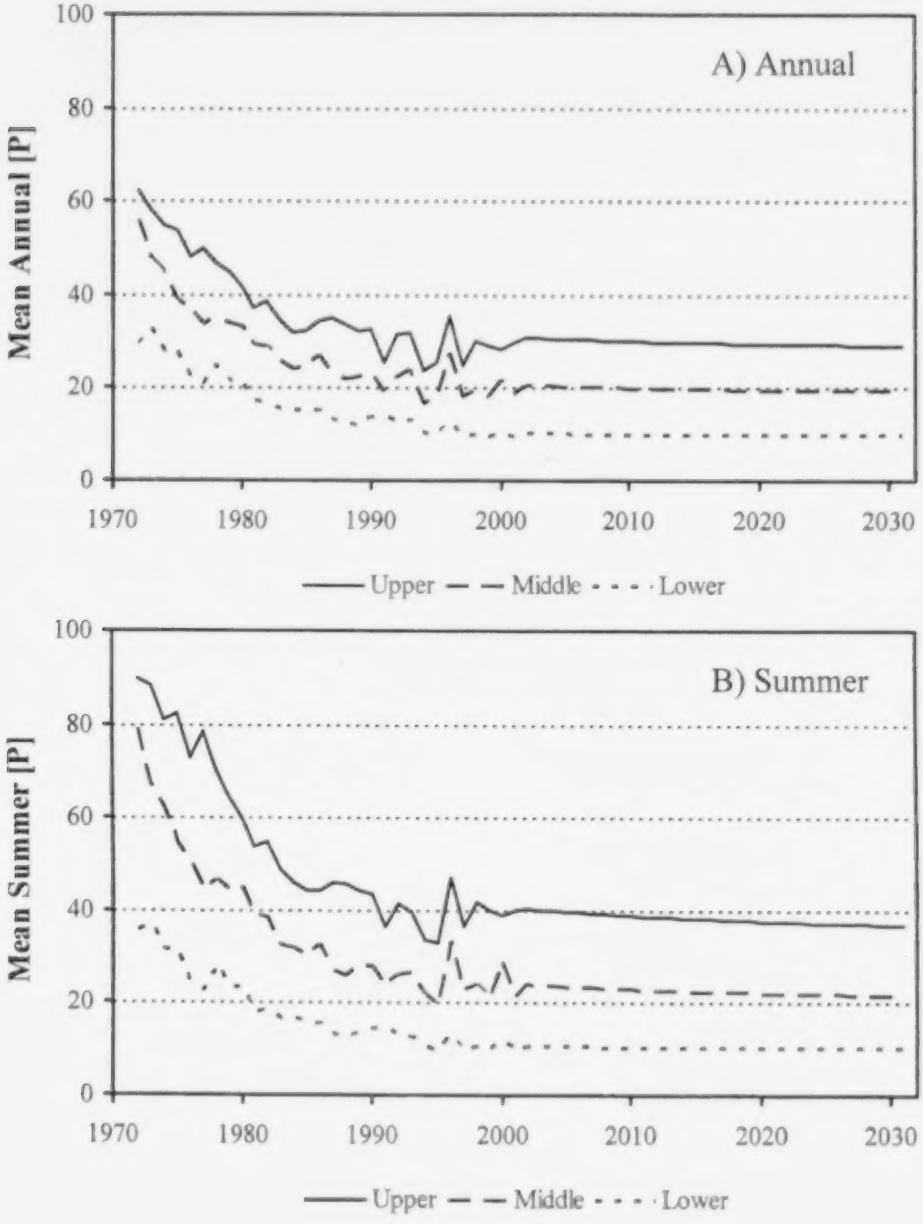


Figure 8. Predicted response (2002-2031) of mean summer [P] ($\mu g\ L^{-1}$) in the upper Bay of Quinte given a range of river runoff conditions and point source loadings held at 2001 levels.

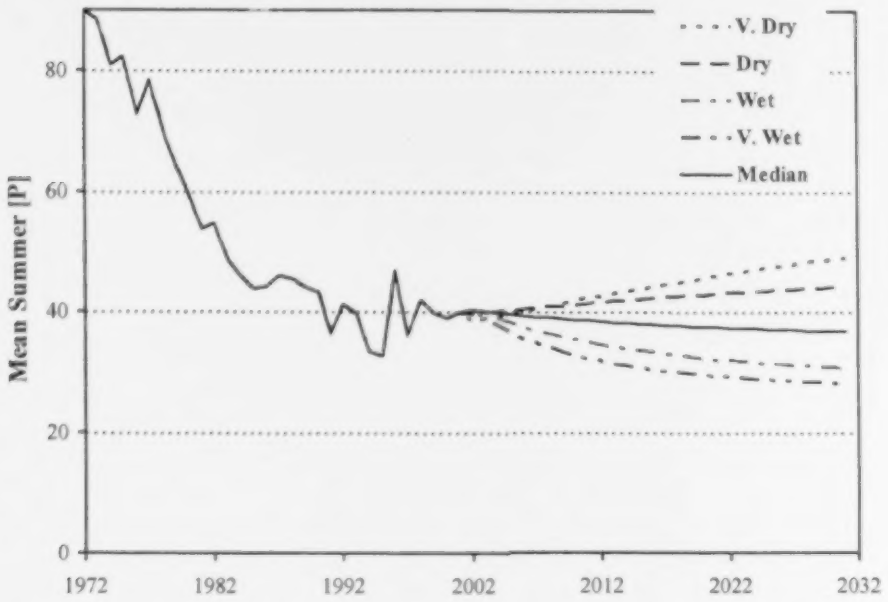


Figure 9. Predicted mean summer [P] ($\mu g\ L^{-1}$) for 2031 in the three (upper, middle and lower) sections of the bay of Quinte given a range of runoff conditions and point source loadings held at 2001 levels.

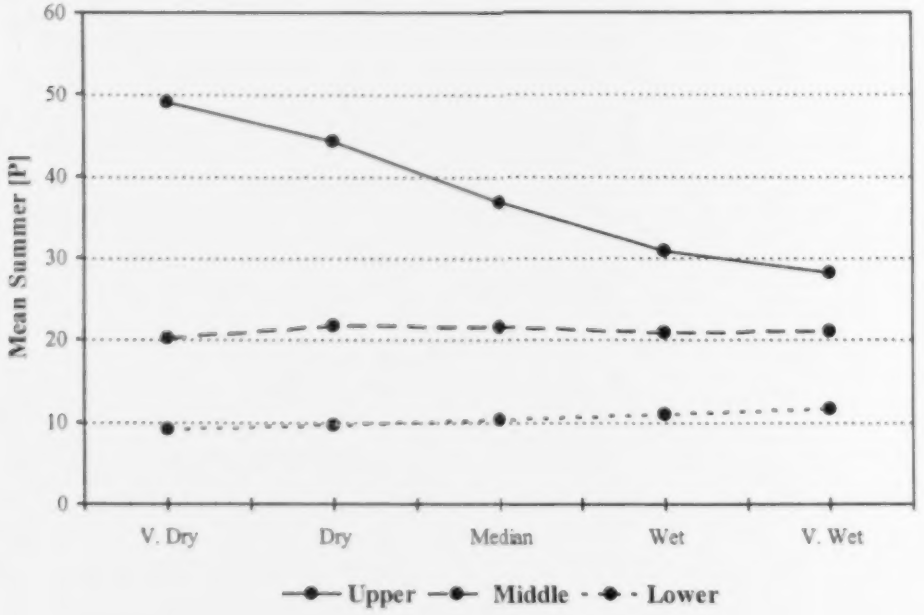


Figure 10. Predicted response (2002-2031) of mean summer [P] ($\mu g\ L^{-1}$) in the upper Bay of Quinte given a range of zebra mussel effect and point source loadings held at 2001 levels with median flows.

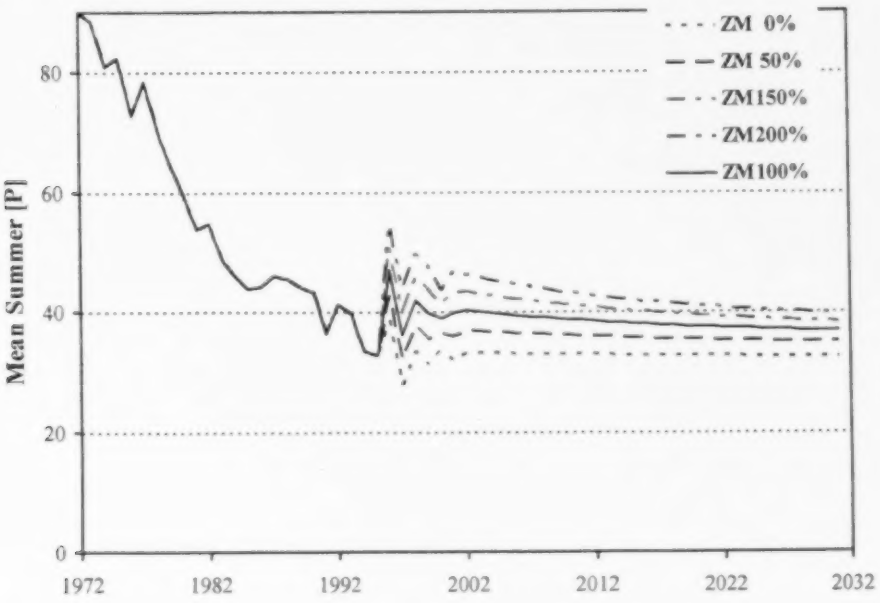


Figure 11. Predicted mean summer [P] ($\mu g\ L^{-1}$) for 2031 in the three (upper, middle and lower) sections of the Bay of Quinte given a range of zebra mussel effects and point source loadings held at 2001 levels with median flows.

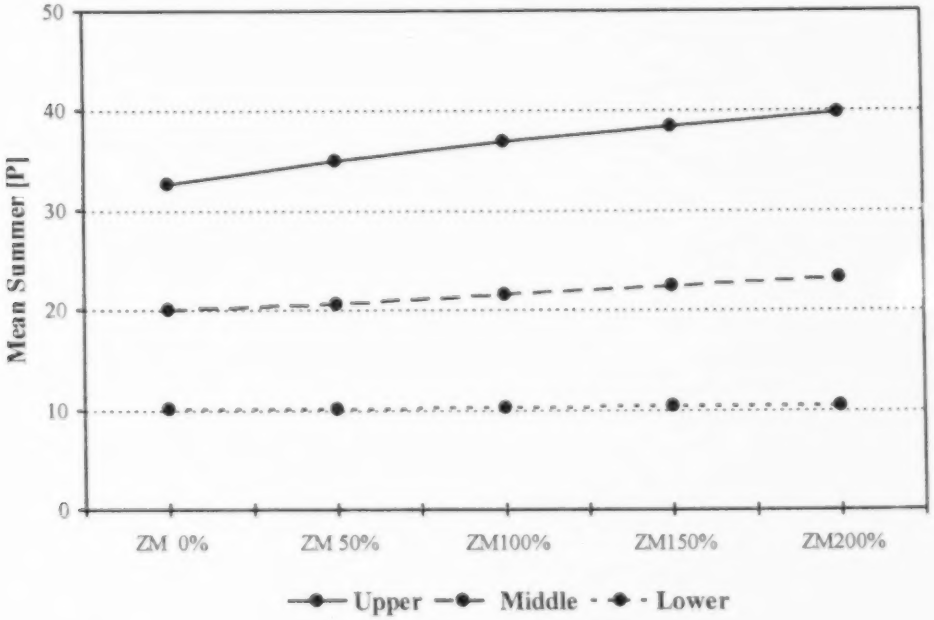


Figure 12. Predicted response (2002-2031) of mean summer [P] ($\mu g\ L^{-1}$) in the upper Bay of Quinte given point source loadings rise to 100% flow capacity in 2010 with either approved (CoA) or actual 2001 (CEF) final effluent concentrations, and with low (25%) and median (50%) flows and median zebra mussels.

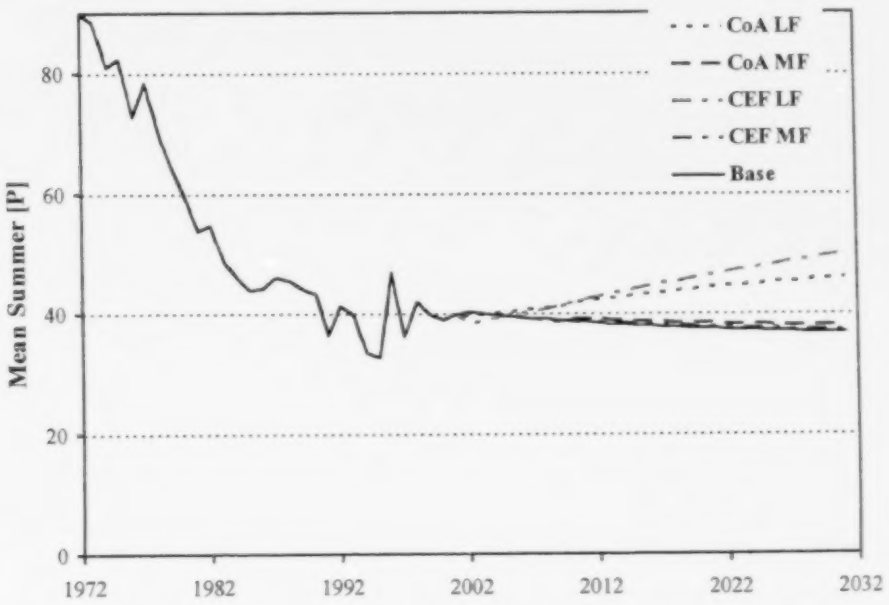


Figure 13. Predicted mean summer [P] ($\mu g\ L^{-1}$) for 2031 in the three sections of the Bay of Quinte given point source loadings rise to 100% flow capacity in 2010 with either approved (CoA) or actual 2001 (CEF) final effluent concentrations, and with low and median flows and median zebra mussels.

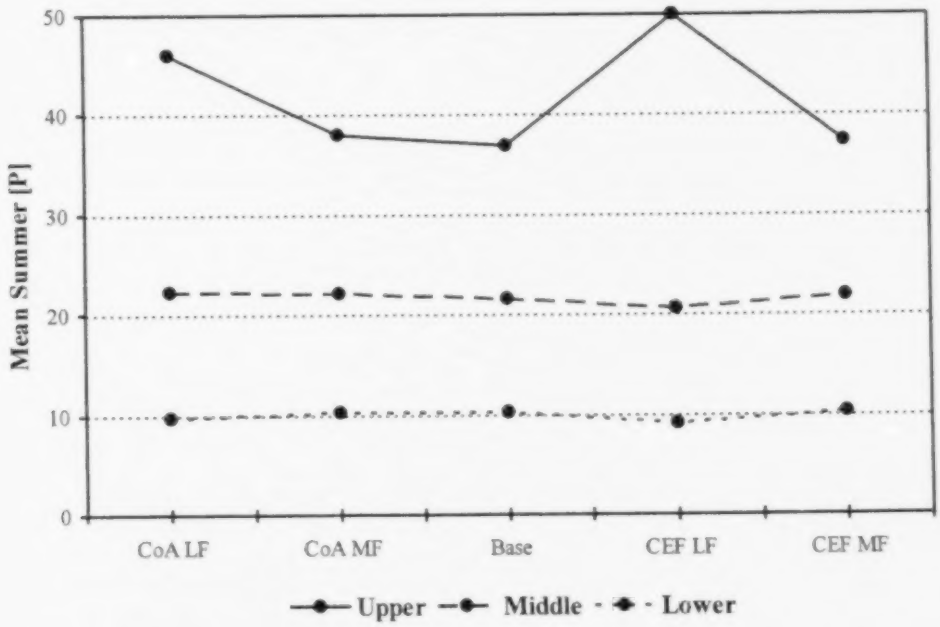


Table 1 Operating specifications for sewage treatment plants discharging into the Bay of Quinte.

STP	Discharges To	Final Effluent P Concentration ($\mu g\ L^{-1}$)	Capacity ($m^3\ day^{-1}$)	Percent of Capacity (2001)
Trenton (Quinte West)	Upper bay	300	15900	41
CFB Trenton	Upper bay	300	3400	61
Belleville	Upper bay	300	54500	55
Deseronto	Upper bay	300	1600	75
Napanee	Upper bay	300	9100	73
Picton	Middle bay	300	5400	83

Table 2. Default values for the all sediment model parameters other than sediment reflux.

Parameter	Units	Value by bay section		
		Upper	Middle	Lower
Settling rate	$m\ day^{-1}$	0.113	0.113	0.113
Accumulation extent [1]	%	35	40	50
Sediment solids density [2]	$g\ cm^{-3}$	2.45	2.45	2.45
Sediment water content [2]	%	90	90	90
Sediment thickness [1]	cm	20	15	10
Initial $[P_S]$ [2]	$mg\ g^{-1}$	1.494	1.494	1.494

[1] approximations based on Minns (1986)
[2] after Minns (1986)

Table 3. Results of alternate combinations of sewage treatment plant flow capacity and final effluent concentration as a means of limiting point source loading to the upper Bay of Quinte, given low (25%) and median (50%) flow scenarios (all scenarios being implemented in 2010).

Scenario		Upper bay	Mean Summer [P] in 2031		% Range
Flow	STP [P]	Load			<43.3 μg L^{-1}
	μg L^{-1}	kg day^{-1}	Low Flow (25%)	Median Flow (50%)	
Actual 2001	300 (CoA)	13.92	44.2	36.8	87.8
Actual 2001	circa 2001	10.06	43.5	36.4	97.2
100%	300	25.35	46.0	38.0	66.3
100%	circa 2001	18.36	44.8	37.2	80.3
80%	300	20.28	45.2	37.4	75.6
75%	300	19.01	45.0	37.3	77.9
100%	250	21.13	45.4	37.5	73.4
100%	200	16.90	44.7	37.1	81.6
100%	150	12.68	44.0	36.7	90.4

Table 4. Predicted mean summer upper bay [P] values in 2031 for different mean Trent River [P] values given low (25%) and median (50%) flow scenarios with the baseline model.

Scenario	Mean summer upper bay [P] in 2031	
	Low flow (25%)	Median flow (50%)
Baseline 2001 loading		
Trent River [P] = 45 ug/l	44.2	36.8
Trent River [P] = 44 ug/l	43.1	35.8
Trent River [P] = 43 ug/l	42.0	34.9
100% CoA 2010		
Trent River [P] = 45 ug/l	46.0	38.0
Trent River [P] = 44 ug/l	44.9	37.0
Trent River [P] = 43 ug/l	43.7	36.0

Appendix A. Equations and built-in data in the STELLA model of phosphorus dynamics in the Bay of Quinte

Averaging_Sink[Section](t) = Averaging_Sink[Section](t - dt) + (Annual_P_Conc[Section] + Summer_P_Conc[Section]) * dt
INIT Averaging_Sink[Section] = 0
Annual_P_Conc[Section] = Section_P_Conc[Section]/365
Summer_P_Conc[Section] = SummerSeason*Section_P_Conc[Section]/153
FourYrCycle = COUNTER(0,1460)
SummerSeason = if YrCycle>=121 and YrCycle<=273 then 1 else 0
TimeBlock = INT(TIME/8)
Year = 1972 + INT(TIME/365)
YrCycle = COUNTER(1,366)
Month = GRAPH(YrCycle)
(1.00, 1.00), (2.00, 1.00), (3.00, 1.00), (4.00, 1.00), (5.00, 1.00), (6.00, 1.00), (7.00, 1.00), (8.00, 1.00), (9.00, 1.00), (10.0, 1.00), (11.0, 1.00), (12.0, 1.00), (13.0, 1.00), (14.0, 1.00), (15.0, 1.00), (16.0, 1.00), (17.0, 1.00), (18.0, 1.00), (19.0, 1.00), (20.0, 1.00), (21.0, 1.00), (22.0, 1.00), (23.0, 1.00), (24.0, 1.00), (25.0, 1.00), (26.0, 1.00), (27.0, 1.00), (28.0, 1.00), (29.0, 1.00), (30.0, 1.00), (31.0, 1.00), (32.0, 2.00), (33.0, 2.00), (34.0, 2.00), (35.0, 2.00), (36.0, 2.00), (37.0, 2.00), (38.0, 2.00), (39.0, 2.00), (40.0, 2.00), (41.0, 2.00), (42.0, 2.00), (43.0, 2.00), (44.0, 2.00), (45.0, 2.00), (46.0, 2.00), (47.0, 2.00), (48.0, 2.00), (49.0, 2.00), (50.0, 2.00), (51.0, 2.00), (52.0, 2.00), (53.0, 2.00), (54.0, 2.00), (55.0, 2.00), (56.0, 2.00), (57.0, 2.00), (58.0, 2.00), (59.0, 2.00), (60.0, 3.00), (61.0, 3.00), (62.0, 3.00), (63.0, 3.00), (64.0, 3.00), (65.0, 3.00), (66.0, 3.00), (67.0, 3.00), (68.0, 3.00), (69.0, 3.00), (70.0, 3.00), (71.0, 3.00), (72.0, 3.00), (73.0, 3.00), (74.0, 3.00), (75.0, 3.00), (76.0, 3.00), (77.0, 3.00), (78.0, 3.00), (79.0, 3.00), (80.0, 3.00), (81.0, 3.00), (82.0, 3.00), (83.0, 3.00), (84.0, 3.00), (85.0, 3.00), (86.0, 3.00), (87.0, 3.00), (88.0, 3.00), (89.0, 3.00), (90.0, 3.00), (91.0, 4.00), (92.0, 4.00), (93.0, 4.00), (94.0, 4.00), (95.0, 4.00), (96.0, 4.00), (97.0, 4.00), (98.0, 4.00), (99.0, 4.00), (100, 4.00), (101, 4.00), (102, 4.00), (103, 4.00), (104, 4.00), (105, 4.00), (106, 4.00), (107, 4.00), (108, 4.00), (109, 4.00), (110, 4.00), (111, 4.00), (112, 4.00), (113, 4.00), (114, 4.00), (115, 4.00), (116, 4.00), (117, 4.00), (118, 4.00), (119, 4.00), (120, 4.00), (121, 5.00), (122, 5.00), (123, 5.00), (124, 5.00), (125, 5.00), (126, 5.00), (127, 5.00), (128, 5.00), (129, 5.00), (130, 5.00), (131, 5.00), (132, 5.00), (133, 5.00), (134, 5.00), (135, 5.00), (136, 5.00), (137, 5.00), (138, 5.00), (139, 5.00), (140, 5.00), (141, 5.00), (142, 5.00), (143, 5.00), (144, 5.00), (145, 5.00), (146, 5.00), (147, 5.00), (148, 5.00), (149, 5.00), (150, 5.00), (151, 5.00), (152, 6.00), (153, 6.00), (154, 6.00), (155, 6.00), (156, 6.00), (157, 6.00), (158, 6.00), (159, 6.00), (160, 6.00), (161, 6.00), (162, 6.00), (163, 6.00), (164, 6.00), (165, 6.00), (166, 6.00), (167, 6.00), (168, 6.00), (169, 6.00), (170, 6.00), (171, 6.00), (172, 6.00), (173, 6.00), (174, 6.00), (175, 6.00), (176, 6.00), (177, 6.00), (178, 6.00), (179, 6.00), (180, 6.00), (181, 6.00), (182, 7.00), (183, 7.00), (184, 7.00), (185, 7.00), (186, 7.00), (187, 7.00), (188, 7.00), (189, 7.00), (190, 7.00), (191, 7.00), (192, 7.00), (193, 7.00), (194, 7.00), (195, 7.00), (196, 7.00), (197, 7.00), (198, 7.00), (199, 7.00), (200, 7.00), (201, 7.00), (202, 7.00), (203, 7.00), (204, 7.00), (205, 7.00), (206, 7.00), (207, 7.00), (208, 7.00), (209, 7.00), (210, 7.00), (211, 7.00), (212, 7.00), (213, 8.00), (214, 8.00), (215, 8.00), (216, 8.00), (217, 8.00), (218, 8.00), (219, 8.00), (220, 8.00), (221, 8.00), (222, 8.00), (223, 8.00), (224, 8.00), (225, 8.00), (226, 8.00), (227, 8.00), (228, 8.00), (229, 8.00), (230, 8.00), (231, 8.00), (232, 8.00), (233, 8.00), (234, 8.00), (235, 8.00), (236, 8.00), (237, 8.00), (238, 8.00), (239, 8.00), (240, 8.00),

(241, 8.00), (242, 8.00), (243, 8.00), (244, 9.00), (245, 9.00), (246, 9.00), (247, 9.00), (248, 9.00), (249, 9.00), (250, 9.00), (251, 9.00), (252, 9.00), (253, 9.00), (254, 9.00), (255, 9.00), (256, 9.00), (257, 9.00), (258, 9.00), (259, 9.00), (260, 9.00), (261, 9.00), (262, 9.00), (263, 9.00), (264, 9.00), (265, 9.00), (266, 9.00), (267, 9.00), (268, 9.00), (269, 9.00), (270, 9.00), (271, 9.00), (272, 9.00), (273, 9.00), (274, 10.0), (275, 10.0), (276, 10.0), (277, 10.0), (278, 10.0), (279, 10.0), (280, 10.0), (281, 10.0), (282, 10.0), (283, 10.0), (284, 10.0), (285, 10.0), (286, 10.0), (287, 10.0), (288, 10.0), (289, 10.0), (290, 10.0), (291, 10.0), (292, 10.0), (293, 10.0), (294, 10.0), (295, 10.0), (296, 10.0), (297, 10.0), (298, 10.0), (299, 10.0), (300, 10.0), (301, 10.0), (302, 10.0), (303, 10.0), (304, 10.0), (305, 11.0), (306, 11.0), (307, 11.0), (308, 11.0), (309, 11.0), (310, 11.0), (311, 11.0), (312, 11.0), (313, 11.0), (314, 11.0), (315, 11.0), (316, 11.0), (317, 11.0), (318, 11.0), (319, 11.0), (320, 11.0), (321, 11.0), (322, 11.0), (323, 11.0), (324, 11.0), (325, 11.0), (326, 11.0), (327, 11.0), (328, 11.0), (329, 11.0), (330, 11.0), (331, 11.0), (332, 11.0), (333, 11.0), (334, 11.0), (335, 12.0), (336, 12.0), (337, 12.0), (338, 12.0), (339, 12.0), (340, 12.0), (341, 12.0), (342, 12.0), (343, 12.0), (344, 12.0), (345, 12.0), (346, 12.0), (347, 12.0), (348, 12.0), (349, 12.0), (350, 12.0), (351, 12.0), (352, 12.0), (353, 12.0), (354, 12.0), (355, 12.0), (356, 12.0), (357, 12.0), (358, 12.0), (359, 12.0), (360, 12.0), (361, 12.0), (362, 12.0), (363, 12.0), (364, 12.0), (365, 12.0)
FlowScen = 2
LevelScen = 2
PrecipScen = 2
SettlingRate = .113
Section_P_Store[Section](t) = Section_P_Store[Section](t - dt) + (Section_P_Inflow[Section] + P_Reflux[Section] - Section_P_Outflow[Section]) * dt
INIT Section_P_Store[Section] = InitialSectionPStore[Section]
Section_P_Inflow[Section] = SectionRiverLoad[Section]+SectionPSLoad[Section]+SectionPrecipLoad[Section]+Section_P_BackInFlow[Section]+SectionUpstreamLoad[Section]
P_Reflux[Section] = if Month>=5 and Month<=9 then SectionArea[Section]*Areal_Reflux_Rate[Section]/1e6 else 0
Section_P_Outflow[Section] = OutFlows[Section]*Section_P_Conc[Section]/1e6+P_Settling[Section]+Section_P_BackOutFlow[Section]
Sediment_P_Store[Section](t) = Sediment_P_Store[Section](t - dt) + (P_Settling[Section] - P_Burial[Section] - P_Reflux[Section]) * dt
INIT Sediment_P_Store[Section] = InitialSedPStore[Section]
P_Settling[Section] = Section_P_Store[Section]*SectionSettlingRate[Section]
P_Burial[Section] = smth1(Sediment_P_Store[Section]*Deposition_Coeff[Section],180)
P_Reflux[Section] = if Month>=5 and Month<=9 then SectionArea[Section]*Areal_Reflux_Rate[Section]/1e6 else 0
AccumulationArea[Section] = SectionArea[Section]*(1-AccumulationExtent[Section]/100)
AccumulationExtent[Upper] = 35
AccumulationExtent[Middle] = 40
AccumulationExtent[Lower] = 50
Annual_Actual_Concs[Section] = Year

```
Areal_Reflux_Rate[Section] = if Year<=1995 then
RefluxA*exp(Sediment_P_Conc[Section]*RefluxB) else
(RefluxA+Zebra_Effect)*exp(Sediment_P_Conc[Section]*RefluxB)
DeltaLevel = DERIVN(Level,1)*DT
DepositionConstant = 1.36137
Deposition_Coeff[Section] = SedimentInput/Sediment_Factor[Section]
Evap = Precip
FConc[Trent] = 45
FConc[Moira] = 18
FConc[Salmon] = 15
FConc[Napanee] = 18
FConc[Wilton] = 36
FFlow[River,Scenario] = YrCycle
FLevel[Scenario] = YrCycle
FPrecip[Scenario] = YrCycle
F_LONT_P_Conc = 8
HConc[River] = TimeBlock
HFlow[River] = TimeBlock
HLevel = if Year <1976 then HLevels[Y7275] else if Year <1980 then HLevels[Y7679] else if
Year <1984 then HLevels[Y8083] else if Year <1988 then HLevels[Y8487] else if Year <1992
then HLevels[Y8891] else if Year <1996 then HLevels[Y9295] else if Year <2000 then
HLevels[Y9699] else HLevels[Y0001]
HLevels[YearBlock] = FourYrCycle
HSectionPSLoad[Section] = TimeBlock
InitialLevel = .320833
InitialSectionPStore[Section] = SectionVolume[Section]*Initial_P_Conc[Section]/1e6
InitialSedPStore[Section] = SedimentMass[Section]*Initial_Sed_P_Conc[Section]/1000
Initial_P_Conc[Upper] = 70.4
Initial_P_Conc[Middle] = 59.8
Initial_P_Conc[Lower] = 24.3
Initial_Sed_P_Conc[Upper] = 1.494
Initial_Sed_P_Conc[Middle] = 1.494
Initial_Sed_P_Conc[Lower] = 1.494
Level = If Year<=2001 then HLevel else if LevelScen=0 then FLevel[Very_Dry] else if
LevelScen=1 then FLevel[Dry] else if LevelScen=2 then FLevel[Typical] else if LevelScen=3
then FLevel[Wet] else if LevelScen=4 then FLevel[Very_Wet] else FLevel[User]
LONT_P_Conc = If Year<=2001 then H_LONT_P_Conc else F_LONT_P_Conc
OutFlows[Upper] = WaterIn[Upper]-WaterOut[Upper]
OutFlows[Middle] = (WaterIn[Upper]+WaterIn[Middle])-
(WaterOut[Upper]+WaterOut[Middle])
OutFlows[Lower] = (WaterIn[Upper]+WaterIn[Middle]+WaterIn[Lower])-
(WaterOut[Upper]+WaterOut[Middle]+WaterOut[Lower])
Precip = If Year<=2001 then HPrecip else if PrecipScen=0 then FPrecip[Very_Dry] else if
PrecipScen=1 then FPrecip[Dry] else if PrecipScen=2 then FPrecip[Typical] else if
PrecipScen=3 then FPrecip[Wet] else if PrecipScen=4 then FPrecip[Very_Wet] else
FPrecip[User]
```

```
Precip_Conc = 15
RefluxA = .02
RefluxB = 4.5
RiverFlow[River] = If Year<=2001 then HFlow[River] else if FlowScen=0 then
FFlow[River,Very_Dry] else if FlowScen=1 then FFlow[River,Dry] else if FlowScen=2 then
FFlow[River,Typical] else if FlowScen=3 then FFlow[River,Wet] else if FlowScen=4 then
FFlow[River,Very_Wet] else FFlow[River,User]
RiverLoad[River] = If Year<=2001 then (HConc[River]*RiverFlow[River])/1e6 else
(FConc[River]*RiverFlow[River])/1e6
SectionArea[Upper] = 136.388e6
SectionArea[Middle] = 49.179e6
SectionArea[Lower] = 71.835e6
SectionBackFlows[Section] = Month
SectionMeanDepth[Section] = SectionVolume[Section]/SectionArea[Section]
SectionPrecipLoad[Section] = SectionArea[Section]*Precip*Precip_Conc/1e6
SectionPSLoad[Upper] = if Year<=2001 then HSectionPSLoad[Upper] else
Source_Loads[Upper]
SectionPSLoad[Middle] = if year<=2001 then HSectionPSLoad[Middle] else
Source_Loads[Middle]
SectionPSLoad[Lower] = if year<=2001 then HSectionPSLoad[Lower] else
Source_Loads[Lower]
SectionRiverFlow[Upper] =
RiverFlow[Trent]+RiverFlow[Moira]+RiverFlow[Salmon]+RiverFlow[Napanee]+WiltonEq[Up
per]*RiverFlow[Wilton]
SectionRiverFlow[Middle] = RiverFlow[Wilton]*(1+WiltonEq[Middle])
SectionRiverFlow[Lower] = RiverFlow[Wilton]*WiltonEq[Lower]
SectionRiverLoad[Upper] =
RiverLoad[Trent]+RiverLoad[Moira]+RiverLoad[Salmon]+RiverLoad[Napanee]+RiverLoad[W
ilton]*WiltonEq[Upper]
SectionRiverLoad[Middle] = RiverLoad[Wilton]*(1+WiltonEq[Middle])
SectionRiverLoad[Lower] = RiverLoad[Wilton]*WiltonEq[Lower]
SectionSettlingRate[Section] = SettlingRate/SectionMeanDepth[Section]
SectionUpstreamLoad[Upper] = 0*OutFlows[Upper]*Section_P_Conc[Upper]
SectionUpstreamLoad[Middle] = OutFlows[Upper]*Section_P_Conc[Upper]/1e6
SectionUpstreamLoad[Lower] = OutFlows[Middle]*Section_P_Conc[Middle]/1e6
SectionVolume[Upper] = 522.6387e6+Delay((Level-InitialLevel)*(SectionArea[Upper]),1)
SectionVolume[Middle] = 271.9802e6+(Level-InitialLevel)*(SectionArea[Middle])
SectionVolume[Lower] = 1780.092e6+(Level-InitialLevel)*(SectionArea[Lower])
Section_P_BackInFlow[Upper] =
(SectionBackFlows[Upper]*Section_P_Conc[Middle])/1e6+(0*LONT_P_Conc)
Section_P_BackInFlow[Middle] =
(SectionBackFlows[Upper]*Section_P_Conc[Upper]+SectionBackFlows[Middle]*Section_P_C
onc[Lower])/1e6+(0*LONT_P_Conc)
Section_P_BackInFlow[Lower] =
(SectionBackFlows[Middle]*Section_P_Conc[Middle]+SectionBackFlows[Lower]*LONT_P_C
onc)/1e6
```

Section_P_BackOutFlow[Upper] = SectionBackFlows[Upper]*Section_P_Conc[Upper]/1e6
Section_P_BackOutFlow[Middle] =
(SectionBackFlows[Upper]+SectionBackFlows[Middle])*(Section_P_Conc[Middle])/1e6
Section_P_BackOutFlow[Lower] =
(SectionBackFlows[Middle]+SectionBackFlows[Lower])*(Section_P_Conc[Lower])/1e6
Section_P_Conc[Section] = (Section_P_Store[Section]/SectionVolume[Section])*1e6
SedimentInput =
(SectionRiverFlow[Upper]+SectionRiverFlow[Middle]+SectionRiverFlow[Lower])*Deposition
Constant/1e11
SedimentMass[Section] = Sediment_Factor[Section]*AccumulationArea[Section]*10
SedimentSolidsDensity = 2.45
SedimentWaterContent = 90
Sediment_Factor[Section] = Sediment_Thickness[Section]*(1-
SedimentWaterContent/100)*SedimentSolidsDensity
Sediment_P_Conc[Section] = 1000*Sediment_P_Store[Section]/SedimentMass[Section]
Sediment_Thickness[Upper] = 20
Sediment_Thickness[Middle] = 15
Sediment_Thickness[Lower] = 10
Source_Loads[Section] = Year
Summer_Actual_Concs[Section] = Year
WaterIn[Section] = SectionRiverFlow[Section]+(SectionArea[Section]*Precip)
WaterOut[Section] = SectionArea[Section]*(Evap+DeltaLevel)
WiltonEq[Upper] = 5.8
WiltonEq[Middle] = 2.1
WiltonEq[Lower] = .7
Zebra_Effect = 0.01
Annual_Actual_Concs[Section] = Year
FFlow[River,Scenario] = YrCycle
FLevel[Scenario] = YrCycle
FPrecip[Scenario] = YrCycle
HConc[River] = TimeBlock
HFlow[River] = TimeBlock
HLevels[YearBlock] = FourYrCycle
HPrecip = GRAPH(TIMEBLOCK)
(0.00, 0.0019), (1.00, 0.00141), (2.00, 0.00241), (3.00, 0.000638), (4.00, 0.004), (5.00, 0.00361),
(6.00, 0.00236), (7.00, 0.00375), (8.00, 0.000313), (9.00, 0.00256), (10.0, 0.00346), (11.0,
0.00126), (12.0, 0.00187), (13.0, 0.00267), (14.0, 0.0001), (15.0, 0.00649), (16.0, 0.0021), (17.0,
0.00101), (18.0, 0.00711), (19.0, 0.00156), (20.0, 0.000162), (21.0, 0.00879), (22.0, 0.00241),
(23.0, 0.0008), (24.0, 0.00153), (25.0, 0.0027), (26.0, 0.00416), (27.0, 0.0041), (28.0, 0.00198),
(29.0, 0.000713), (30.0, 0.0016), (31.0, 0.00302), (32.0, 0.0001), (33.0, 0.00388), (34.0,
0.00606), (35.0, 0.0002), (36.0, 0.00604), (37.0, 0.00123), (38.0, 0.0067), (39.0, 0.00035), (40.0,
0.0007), (41.0, 0.00454), (42.0, 0.00299), (43.0, 0.00636), (44.0, 0.00146), (45.0, 0.00503),
(46.0, 0.00105), (47.0, 0.00118), (48.0, 0.00181), (49.0, 0.00496), (50.0, 0.000788), (51.0,
0.00118), (52.0, 0.00045), (53.0, 0.00264), (54.0, 0.00293), (55.0, 0.00635), (56.0, 0.0046),
(57.0, 0.00524), (58.0, 0.00105), (59.0, 0.0021), (60.0, 0.00489), (61.0, 0.00266), (62.0,
0.00143), (63.0, 0.00149), (64.0, 0.00243), (65.0, 0.00296), (66.0, 0.00085), (67.0, 0.00685),

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HSectionPSLoad[Section] = TimeBlock

H_LONT_P_Conc = GRAPH(Year)

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SectionBackFlows[Section] = Month
Source_Loads[Section] = Year
Summer_Actual_Concs[Section] = Year